Tectonic Studies Group Annual General Meeting 2014

Cardiff University, 6-8th January

Abstracts

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Edited by: Tom Blenkinsop, Ben Manton, Dan Morgan, and Chris Wild

Oral Presentation Programme

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11.20-11.40	M.Heather	Temporal Evolution of Fault Architecture and Diagenesis: Coupling Between Fault Development and Fluid Flow
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The Tectonic Studies Group is grateful to the following for helping to organise TSG 2014:

Tiago Alves

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Debbie Skene

Chris Wild

Christine Williams

Georgina Worral

Oral Presentations

Day 1

Monday 6th January, 2014

From mechanical modelling to seismic imaging of faults

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Although typically interpreted as 2D surfaces, faults are 3D narrow zones of highly and heterogenously strained rocks, with petrophysical properties differing from the host rock. 3D fault structure and properties are primary controls on fluid flow in faulted reservoirs. We describe a synthetic workflow to assess the potential of reflection seismic data for imaging fault structure and properties. The workflow is based on a discrete element model (DEM) of faulting, simple relations to modify the base acoustic properties of the model based on volumetric strain, and a ray-based algorithm (pre-stack depth migration or PSDM). Parameters such as wave frequency and illumination direction and their impact on the resulting seismic image are evaluated with the PSDM simulator. We illustrate the application of the workflow to a large 100 m displacement normal fault in an interlayered sandstone-shale sequence in 2D and 3D. In 3D, we also explore the impact of linearly varying fault displacement along strike. Although the DEM does not target processes at the grain scale, but rather meter size bulk strain, it produces realistic fault geometries and strain fields in 2D and 3D. Seismic images of these models are highly dependent on illumination direction and wave frequency. Specular illumination highlights the areas outside the fault zone but still fault related diffractions can be identified. Footwall directed illumination produces low amplitude images. Hanging wall directed illumination highlights the shale layers within the fault zone. Resolution and the accuracy of interpreted reflectors are directly proportional to wave frequency. At high frequencies (40 Hz), there is a direct correlation between seismic amplitude variations and changes of input acoustic properties. At these high frequencies, seismic amplitude anomalies can predict the extent of faulting and the internal properties of the fault zone, which are critical parameters for assessing the sealing capacity of the fault.

Fault zone architecture and weakening mechanisms of the southern Dead Sea Fault System: mineralogical and microstructural observations

Siân Evans[1], Bob Holdsworth[1], Eddie Dempsey[1], Nicola de Paola[1], Jonny Imber[1], Shmuel Marco[2], Rami Weinberger[3]

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The mechanical weakening processes involved in the development of major crustal fault systems have been widely documented and it is recognised that clay-bearing fault gouges frequently have a significant influence on fault strength. However, it is less well-known how mechanical processes, such as cataclasis and the bulk translation of fault rock materials along fault zones (e.g. 'smearing'), interact with chemical processes, such as clay mineral transformations and phyllonitisation during gouge development.

Six exhumed fault sections have been studied from the southern portion of the Dead Sea Fault System, an active continental transform fault that has accumulated 105 km of sinistral displacement since the mid-Miocene. The faults vary in length, displacement and associated lithologies, and have developed into fault zones with very variable characteristics. The fault zone architecture and microstructural nature of two exhumed sections, the Tzefahot and Shelomo faults, are discussed here. These sinistral transtensional faults juxtapose Precambrian basement rocks with Mesozoic cover rocks forming major, graben-bounding structures exceeding 10 km in length with estimated displacements of 725 – 1190 m (Tzefahot Fault) and 7534 – 9919 m (Shelomo Fault).

Both faults have a fault core of significant width (1 m and 4 m), with associated damage zones (> 10 m across). The cores of the two faults are composed of well-defined, centimetre – metre-scale domains, which microstructural observations reveal to be interlayered cataclasite and clay 'gouge', with evidence of mechanical intermixing at meso – micro scales. These domains are moderately – strongly foliated with sinistral σ-type clasts. Microstructures observed include brittle microfracturing and evidence of grain-size reduction and rounding, 'ductile' folds within clay material and evidence of chemical alteration (feldspar breakdown to phyllosilicates). The implications for fault zone processes and weakening will be discussed.

Inherited structural and lithological basement controls on the development of thrust faults in the Northeast Tibetan Plateau.

Rowan Vernon[1], Dickson Cunningham[1,2], Zhang Jin[3], Richard England[1].

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The Qilian Mountains of the northeast Tibetan Plateau represent one of the most actively deforming regions of the Plateau, and may provide an analogue for the evolution of its older regions. The crust of the Qilian Mountains is an orogenic collage of island arc derived meta-volcanic and sedimentary rocks, accreted to the North China Craton during the Palaeozoic. This terrane consolidation was followed by relative tectonic quiescence during the Mesozoic, when thick sedimentary sequences were deposited in large inland basins. Northeast-directed compression related to the Indo-Asia collision began here in the early Miocene. The resulting northwards-propagating deformation is characterised by uplift of fold-thrust mountain ranges which splay south-eastwards from the sinistral northeast-trending Altyn Tagh Fault (ATF).

In this project, we investigate the extent of inherited structural and lithological controls on the post-Oligocene tectonics around the Changma Basin (Fig. 1) at the very northeast corner of the Plateau, where the ATF forms a triple junction with the Qilian Nan Shan. Our research involves synthesis of previous geological and geophysical data, remote sensing analysis and structural mapping along key transects.

The Changma Basin is being uplifted through thrusting at the front of the Qilian Nan Shan and inverted due to back-thrusting of the Yumen Shan, related to transpression against the ATF. It is not possible to trace major structures from the basin into the surrounding ranges to demonstrate unequivocal evidence of basement reactivation. Field data and previous geological mapping show that some of the main range-building thrusts are approximately strike-parallel to basement structures within the ranges, while some are strongly discordant to these structures. Pre-existing foliations are exploited by some range-bounding faults, but intra-range reactivation of older fabrics has not been observed. In ranges containing thick limestone units intra-range uplift is accommodated by thrust faults both within and below the limestones, however in ranges lacking these units uplift is focused on the range-front.

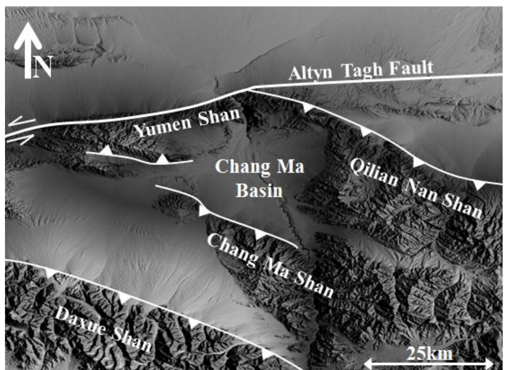

Figure 1; Topographic map showing the mountain ranges and major range-bounding faults surrounding the Changma Basin.

These observations suggest that inherited basement structures and specific lithologies exert varying degrees of control on the development of thrust faults and the post-Oligocene uplift of mountain ranges in the northeast Tibetan Plateau.

Keywords: Northeast Tibet, Altyn Tagh Fault, Qilian Shan, plateau growth, reactivation

Temporal Evolution of Fault Architecture and Diagenesis: Coupling Between Fault Development and Fluid Flow

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Constraining the dynamic feedback between deforming porous media and fluid is crucial for understanding hydrocarbon reservoirs, CO_2 storage sites and other evolving porous media. In particular, predicting complex fault architecture at depth, currently relies on deterministic algorithms, that do not take account of these dynamic coupling. For instance creation of permeability due to fracturing may permit fluid flow to enter a fault zone, resulting in mineralisation (strengthening) or alteration (weakening) of the fault and host rocks. The resulting changes in rock strength may enhance or retard further fracturing and may even result in a switch of deformation mechanism.

Temporal evolution of fluid flow through faulted porous rocks has been studied in a field site SE USA. The field area presents a well-exposed fault system that contains evidence for flow of multiple phases of groundwater with varying chemistries and flow of hydrocarbons. By detailed field mapping and microstructural observations of the fault rocks and of the evidence for fluid flow (e.g. bleaching and hydrocarbon staining) we unravel the fluid flow history and evolving flow properties of the rocks.

The 16km long fault presents an erosional scarp of up to 20m high at its centre. This scarp is dissected with canyons that permit cross-sectional views of the fault and associated alteration to be mapped. The field area contains two general classes of lithology. In porous sandstones, deformation is accommodated by deformation bands and fractures. In tight limestones and siltstones deformation is accommodated by fracturing and the formation of clay-rich fault rocks. Evidence for multiple fluid flow events can be observed. Hydrocarbon staining is confined to the coarsest grained layers in the sandstones, and to fractures in all lithologies. Bleaching occurs around small fractures in the fault damage zone and within structural terraces in the fault zone.

We present evidence of the evolving structural and geochemical history of the fault zone and discuss how such data can be used to improve predictive capability of fault zone properties at depth where the faults have accommodated syn-faulting fluid flow.

Mass-transport deposits as markers of fault propagation and structural decoupling on continental margins (Espírito Santo Basin, SE Brazil).

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This work uses high-quality seismic data to assess the importance of mass-transport deposits (MTDs) as markers of fault propagation. We mapped three distinct MTDs and several fault families on the continental slope of Espírito Santo, SE Brazil. Fault mapping was based on seismic attributes such as seismic coherence, structural smoothing and ant tracking. Genetically-related fault families were evaluated in terms of their throw-depth (t-z) and throw-distance (t-x) gradient curves. Based on their orientation and degree of interactions with MTDs, important faults in the study area include decoupled and non-decoupled faults. A key result in this paper is that fault propagation was hindered by Eocene-Early Miocene MTDs in the south eastern part of the study area. Throw-depth variations from these faults are associated with: a) lithologic controls resulting from the presence of MTD strata, b) fault segmentation and c) reactivation by dip linkage. Importantly, faults decoupled by MTDs have quasi-elliptical t-x profiles and show smaller cumulative throw values and fault propagation rates when compared to their non-decoupled counterparts. Our work is important as it shows that MTDs can be used as a marker to estimate structural decoupling between distinct fault sets. In addition this work shows, for the study area, that structural compartments in MTDs are generated by the interconnection of E-W and NW-SE oriented decoupled faults. Compartments with throws >30 m form potential barriers to fluid flow provided other sealing criteria are fulfilled, namely the presence of essentially muddy low porosity strata in MTDs.

Structural mechanisms of vein formation and evolution in a low sulfidation epithermal vein gold deposit, Kestanelik, Turkey

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Gold mineralization in low sulfidation epithermal deposits occurs predominantly as veins or stockworks. Epithermal ore fluids rise from depth along structural pathways at high temperatures under enough pressure to prevent boiling. Mineralization occurs when the pressure drops suddenly (for instance, through faulting), which instantly triggers boiling and causes the ore fluids to precipitate their minerals into any available open space. When the system is again sealed, pressure begins building again till the next rupturing event occurs and the mineralizing process reoccurs. This active episodic process breaks up vein fillings deposited in previous stages, covers them with new fillings and gives epithermal veins their characteristic repeated banding and breccia textures. Therefore structures play major role in the localization of gold, and the processes of rupturing causing the formation of permeability pathways where the hydrothermal outflow is focused. Understanding the controls on the repeating mineralization processes should provide effective tools for predicting where the gold is enriched in low sulfidation epithermal gold deposits.

The prospect is a well-preserved low sulfidation epithermal gold vein/breccia system located in NW Turkey. It contains seven exceptionally well-exposed huge auriferous epithermal quartz veins and vein breccias. The prospect is transacted by a steeply incised valley resulting in good up-dip sections of some veins. Additionally, exploration drill cores through all the veins penetrate up to 150 m below the valley floor giving over 400m vertical "exposure" of the vein textures. Textures in the drill cores and surface veins show the full range of quartz textures that represent deposition at temperatures of 300 °C to 100 °C. Observation of textures and breccias on the vein outcrops and in drill cores indicate that boiling was a probable mechanism for gold deposition and multiple episodes of fluid flow associated with different mineralizing phases took place in the prospect.

We investigate the structural controls on the multi-phase history of vein emplacement using detailed structural data, and examination and mapping of vein textures and breccias. Ongoing work aims to understand the cross-cutting and structural relationship among different mineralizing episodes by examining the quartz textures and breccias and mapping their spatial distribution on vein outcrops and in drill cores.

This study emphasizes the importance of understanding the structural controls on the multi-event history of vein emplacement for gold exploration on the mine and regional scales. In addition, the results will shed light on the behaviour of hydrothermal fluids at high crustal levels.

To Seep or Not to Seep? A comparison of CO_2 bearing reservoirs in Italy

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The risk of CO_2 leakage from engineered geological stores - where injected CO_2 must remain at depth for many thousands of years - can be minimised if potential storage site properties are guided by understanding of CO_2 retention and migration mechanisms within the Earth's crust. Here a study of natural CO_2-rich reservoirs in Italy (CO_2 > 90 %) which have variable CO_2 properties provides insight into mechanisms of long term storage site performance.

The CO_2 -bearing reservoirs studied here exhibit a range of conditions (depth, geothermal gradient, fluid pressure) but their characteristics are broadly similar: carbonate reservoir units are capped by thick, heterogeneous, tectonically stacked flysch overburden. Some reservoirs have surface CO_2 seeps that are typically clustered, located close to faults and are inferred to leak, whereas subsurface reservoirs with no surface seep expression and are inferred to be intact. We show that the main factor governing the sealing properties of a reservoir is related to the overburden pressure conditions rather than the physical state of CO_2. No seeps are spatially located above reservoirs with overpressured overburden; which is symptomatic of a reservoir seal (perhaps enhanced by evaporite bearing caprocks). If fluids in the overburden are at hydrostatic pressures, surface CO_2 seeps are observed above the reservoir. These seeping reservoirs are located close to modern (max ~18 Ka) extensional fault systems which may have equilibrated the fluid pressure conditions.

Two 'leaking' case studies are examined in detail: a) Pieve Santo Stefano reservoir (3.6 km deep) in the Northern Apennines close to the *Caprese Michelangelo* CO_2 seep cluster and b) the Monte Forcuso CO_2 reservoir (~1.1 km deep) in the Central-Southern Apennines which lies beneath *Mefite D'Ansanto,* the most effusive known CO_2 seep. We model CO_2 behaviour during conservative fluid ascent to the surface, then assess the threshold permeabilities required for then in the reservoir to migrate through the overburden at the range of surface seep rates observed (in either dissolved or free phase). We find that feasible leakage mechanisms are determined by the density of the CO_2 in the reservoir. Dense CO_2 fluids do not require high permeability pathways to leak from the reservoir at the observed seep rates. However, modelled changes in CO_2 properties will lead to fluid channelling along high permeability pathways (i.e. faults), and enhanced seepage areas.

These findings stress the importance of an intact low permeability seal, especially at storage sites with denser CO_2 allowing small leakage volumes of CO_2 to lead to significant surface seepage. Understanding the mechanisms enabling or preventing CO_2 escape will reduce uncertainty of overburden integrity and inform storage site selection, monitoring, and leakage mitigation procedure.

Felt seismicity, Fracking, and Faulting: How do they relate?

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Much of microseismicity associated with hydraulic fracturing, reported very widely and used to map the progress of fractures, is unsurprisingly Mode-1(Tensile) failures which generally have very low magnitudes (<0.5 ML). Rare but important cases of felt seismicity induced by hydraulic stimulation ('fracking') have been observed recently, from Blackpool, UK, the Horn River Basin, British Columbia, Canada and potentially, Oklahoma. This paper discusses the sequence of 55 felt earthquakes (maximum magnitude 2.3ML) observed during low volume, short duration, hydraulic fracturing of the first shale gas exploration in the UK.

Approximately 50 prior and subsequent seismic events with magnitudes > 1 and signatures almost identical to the felt events were observed during the initial hydrofracturing stages before the felt seismicity. The similarity between waveforms indicates that they all originated from the same source and travelled identical travel paths and were tightly localized. Hypocentral locations and focal mechanism for representative seismic events were calculated. A new 3D seismic survey shows that the event hypocenter and the focal mechanism correlate strongly with an identifiable fault. Induced seismicity is observed from mining, oil and gas extraction, reservoir impoundment and most recently from ground water extraction in southern Spain and perhaps from gas storage at the Castor field, Spain and understanding the causative geomechanical processes and strategies to mitigate it are important. Usually, the stimulus is caused by pore pressure perturbations during large-volume, long-term injection of fluids (oil/water/gas) which change the normal stress on faults, inducing slip which manifests as an earthquake, with magnitude dependent on the area of fault and the amount of slip. The onset of these events can be many kilometers distant and after many years of pumping depending on when the disturbance encounters a favourably oriented fault. This is the case for the recent observed increase in seismicity (>5ML) reported from the mid US associated with long-term, waste-water disposal.

The other postulated but rarely observed mechanism is direct injection of fluid into a nearby fault effectively reducing the friction and triggering an earthquake.

It is most likely from the Gutenberg-Richter statistics of the seismicity where we see a low-b value (i.e. a disproportionately high number of larger events) and the very rapid response to injection that we are seeing this latter behaviour here giving a unique opportunity to observe and understand the mechanisms which cause shear failure mechanisms at other than laboratory scale Tri-Axial test scales.

The geometry of the Snap Lake kimberlite intrusion, NWT, Canada

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Underground exposures and drillhole data from the Snap Lake Diamond Mine (De Beers Canada) permit the detailed examination of the geometry and structural characteristics of a Cambrian age (523 Ma) sheet-like, kimberlite body: the Snap Lake intrusive (SLI). Drilling has delineated the SLI over an area of approximately 6km^2, where it is known to be a shallowly-dipping, highly-segmented, sheet intrusion, hosted by highly-deformed metavolcanics, metaturbidites and metagranitoids of the Archaean Slave Province. Three moderately to vertically dipping sets of faults are identified in the project area, based on their orientation, kinematics and cross-cutting relationships, including the regionally extensive Snap-Crackle Fault System. Fault activity predominantly occurred prior to 1.27 Ga and therefore predates kimberlite emplacement.

The SLI has an overall dip of approximately 15ºE and is typically 1-3m in thickness. Individual segments are largely discordant to depositional and deformation fabrics in the host rocks. At scales of metres to tens of metres, the intrusive can be divided into shallowly dipping segments and more steeply dipping ramps, where the segments have linked. Over the area of the mine development, the ramps are oriented relatively consistently towards the SW or WSW and, as they represent the linkage between originally distinct segments, they reflect the propagation direction of the intrusive.

Recognisable separations between linked and unlinked intrusive segments range from centimetres to decimetres, and have lateral spacings ranging between 5 and 50m. The vertical separation between adjacent segments across a single ramp may increase or decrease in magnitude along its length, resulting from the initial bifurcation and coalescence of fracture segments. Analysis of the ratio of the local intrusive thickness relative to the thickness of splays that protrude beyond ramps linking adjacent segments suggests that the majority of segment linkage occurred at an early stage. The data show that all pairs of segments vertically separated by less than half the local intrusive thickness are linked, and that the majority of segments were linked after only 20% of inflation of the intrusive.

Interaction of the intrusive with minor pre-existing faults is negligible. However, complex intrusive geometries occur close to several major faults. Thick fault zones appear to have compartmentalised the propagation of the intrusives into non-coplanar segments across the faults. Additionally, in the footwall of a moderately-dipping fault, locally intruded by the kimberlite and reactivated as a syn-intrusive reverse fault, the intrusive thins and displays irregular geometries. Thinning of the kimberlite is interpreted to result primarily from the conservation of vertical displacement beneath the fault.

A model is presented for the development of the SLI that is consistent with its geometrical characteristics.

The intrusion 'space problem': a comparative case study of accommodation and deformation structures associated with the emplacement of the Maiden Creek and Trachyte Mesa satellite intrusions, Henry Mountains, Utah

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Most studies of magmatic intrusions concentrate on geometry and internal architecture: only a few pay particular attention to emplacement-related deformation structures in the host rock that record how magma is accommodated within the crust, i.e. the 'space problem'. This research aims to develop a greater understanding of how igneous intrusive bodies are emplaced and accommodated within the shallow crust, using classic exposures found in the Henry Mountains, Utah.

Two satellite intrusions to the Mt Hillers intrusive centre show highly contrasting geometries, host-rock deformation structures, accommodation structures and apparent emplacement mechanisms. Trachyte Mesa, the most distal satellite intrusion of Mt Hillers, has a relatively simple elongate (NW-SE) geometry, concordant with the Entrada Sandstone it intrudes. The intrusion is comprised of multiple, stacked intrusive sheets. Syn-emplacement deformation structures observed in the host rocks consist of a conjugate set of intrusion margin-parallel deformation bands and extensional brittle faults, the latter occurring at the tips of intrusive sheets. These structures, along with a post-emplacement set of intrusion margin parallel and perpendicular tensile joints, indicate extensional strain normal to the intrusion margin, consistent with a two-stage growth mechanism for the overall intrusion.

In comparison, Maiden Creek, more proximal to the intrusive centre, shows a more complex elliptical shape with several finger-like lobes. Detailed outcrop studies across two neighbouring lobes have identified a sub-horizontal shear zone that runs along the top contact of each intrusive lobe. This shear zone separates low-/moderately-deformed sandstones above from highly deformed sandstones below and between the two lobes, hence acting as a detachment zone. Strain within the highly deformed sandstones is dominated by compressional faults, fractures and fabrics that point to a 'bull-dozing' mechanism for lobe emplacement. Fabrics (stretched phenocrysts) within the igneous rock, seen on the upper surface of the intrusive lobes directly beneath this shear zone, show that the shear zone was contemporaneous with magma emplacement. The shear zone therefore appears to have played a critical role in accommodating magma emplacement.

Hydrothermal vent size and distribution controlled by feeder, 'saucer-shaped' sills

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Along the Norwegian Atlantic Margin, hydrothermal vents associated with sills are a ubiquitous feature between the marginal high at the continental-oceanic crust boundary, and the non-magmatic continental interior. Here, we report on >160 hydrothermal vents associated with 'saucer-shaped' basaltic sills, observed in a high resolution 3D seismic data set covering 1000 km^2. Hydrothermal vents, also known as breccia pipes, form when host-released fluids propagate upwards, and then erupt at the seafloor.

The vents observed are generally circular. Their maximum diameters vary from 5 km to less than 80 m, whereby the seismic resolution limit is reached. Vent size is primarily controlled by sill depth, vent spacing and sill thickness. For instance, larger vents are found to be more widely spaced and are located above deeper, thicker sills. However, the variation in vent size is also affected by secondary factors including the fluid content of the host and how fluids are released.

Vent location is strongly associated to sill margins. Sills are highly transgressive so that sections of their margins are elevated in comparison to their interiors. In special circumstances, some vents are found above sill interiors, such as where there are localised high regions, and where sill depth changes abruptly in the form of steps.

Hydrothermal vents occur world-wide and are associated with a wide range of magma types; gasses released from hydrothermal vents have been associated with global warming and climate change. Understanding hydrothermal venting will aid in the understanding of magma propagation, fluid flow in basins as well as the thermal history of basins.

Day 2

Tuesday 7th January, 2014

Polymodal fractures: A new angle on failure

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Our current understanding of rock failure is dominated by the magnitude of stress at yield, but failure also has intrinsic geometrical attributes i.e. the orientations of the failure surfaces with respect to the applied loads (or strains). Accurate predictions of failure surface orientations are critical for the quantification of fracture connectivity, which in turn exerts a huge influence on bulk permeability and bulk strength. The Mohr-Coulomb model for failure, and many others, predict bimodal or conjugate failure surfaces oriented parallel to the intermediate principal stress (sigma 2) and at acute angles to the maximum principal stress (sigma 1, most compressive). And yet these failure criteria cannot predict fracture patterns that accommodate general 3D strains, which must be the most common situation on a curved Earth. Field and laboratory studies have already shown the existence of polymodal (or quadrimodal) failure surfaces, with 4 or more sets of contemporaneous brittle shear fractures in a range of rock types. In this contribution, the laboratory experimental evidence is reviewed and a new model for the formation of polymodal fracture sets is proposed. New work is needed to fully explore more realistic stress and strain boundary conditions, and their impact on the final fracture pattern and fracture connectivity.

Chaotic breccia zones on the Pembroke Peninsula, South Wales: collapse into voids along dilational faults?

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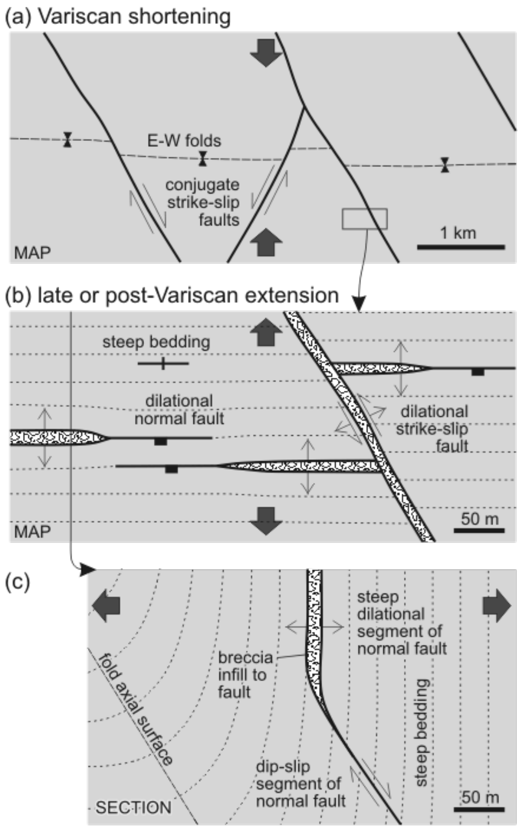
Chaotic breccias and megabreccias – locally called gash breccias – hosted within the Pembroke Limestone Group (Visean, Mississippian, lower Carboniferous) of southwest Wales are re-mapped along with spatially-related crackle and mosaic breccias.

Of 13 studied megabreccia bodies, seven lie along steep, NNW- or NNE-striking strike-slip faults originating during north-south Variscan (late Carboniferous) shortening, though reactivated during later extension. Four megabreccia zones are conformable with E-W striking, steeply-dipping bedding, and two have irregular or indeterminate margins. The bedding-parallel fissures are interpreted as the dilational tips of listric normal faults, and the cross-strike faults as transtensional transfer zones.

Within the megabreccia zones, internal kink folds and detached bedding slabs with sub-horizontal fabrics suggest brecciation by gravitational collapse into opening fissures rather than by attritional cataclasis along the faults. Most fissures have geometrically matched margins produced by this dilational faulting.

Analogous fills to dilational faults occur for 150 km to the east within the Bristol Channel Basin. The most likely age for the main fissure extension and fill is late Triassic, based on dated fissure fills at the eastern end of the basin. Only locally do the Pembrokeshire breccia zones host solutional voids with indented margins, filled with bedded sediment or breccia.

The Pembroke megabreccias add to the catalogue of collapse breccias into voids formed along upper crustal faults. These rocks blur the distinction between fault rocks formed by deformation and those formed by redeposition along or adjacent to faults.



a) Diagrammatic map of folds and conjugate strike-slip faults formed by north-south Variscan shortening. b) Map of postulated post-Variscan north-south extensional reactivation of Variscan faults and steepened bedding. c) Cross-section across a dilational normal fault that steepens to parallel bedding at shallow depths.

Introducing a new terminology for vein wall-foliation crosscutting relationships in foliated rocks as a tool to unravel vein kinematics

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Commonly, a pre-existing foliation (*i.e.* 'host-fabric element' according to Passchier 2001), crosscut by a regular, straight-walled vein (*i.e.* 'cross-cutting element' according to Passchier 2001), resulting from an opening fracture, can be followed across the vein. If this simple geometrical rule does not apply, the non-matching vein wall-foliation crosscutting relationship indicates a shape modification prior to complete infill of the vein.

We introduce a novel approach in an attempt to objectively describe the geometrical relationship between the vein wall and the crosscut foliation. First, we introduce an arbitrary **directional sense** to the foliation in order to define in which direction the foliation continues away from the vein wall. Secondly, two types of **vein-wall segment** (WS) can be labelled, each characterised by an opposite directional sense of the foliation joining the vein wall (*i.e.* x- and y-joining vein-wall segments, with x and y arbitrarily chosen, but opposite, directions; *e.g.* north- (NWS) and south-joining vein-wall segments (SWS) in the High-Ardenne slate belt case study). Thirdly, we define two types of **switch point**, *i.e.* the point (in 2D sections) where the vein-wall segments switches from directional sense. In the case of an **internal switch point** (ISP) the directional continuity of the foliation is achieved internally, *i.e.* inside the vein. ISPs correspond to the original vein/fracture tip. In the case of an **external switch point** (ESP) the directional continuity of the foliation is achieved externally, *i.e.* inside the host rock. Foliation is thus comprised in between two vein-wall segments flanking the switch point. ESPs commonly relate to branching points of vein offshoots. A fundamental assumption in our approach is that the switch points do not change during the progressive deformation, by *e.g.* fracture tip propagation in the unaffected host rock.

The application of this particular labelling of vein-wall segments and switch points offers a transparent and standardized procedure to visualise the progressive shape modification of 'deforming cavities', *e.g.* fluid-filled opening fractures, and to facilitate a retrodeformation (by 2D line-length balancing) of the original 'parental fracture'. We will demonstrate this procedure in the unravelling of the kinematics of discordant quartz veins, comprised in a late-orogenic extensional shear zone in the slates of the High-Ardenne slate belt (Belgium).

This purely geometrical terminology is, moreover, applicable for all types of 'cross-cutting elements' (*e.g.* veins, flanking structures, intrusions) transecting a 'host-fabric element' (*e.g.* foliation), that are subsequently affected by a shape modification prior to complete infill and/or solidification.

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Strain analysis from objects with a random distribution: a generalized center-to-center method

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Existing methods of strain analysis such as the centre-to-centre method and the Fry method estimate strain from the spatial relationship between point objects in the deformation state. They assume a truncated Poisson distribution of point objects in the pre-deformation state. Such an ideal situation is not frequently met in practice, for which numerous modifications about the methods have been developed ever since.

A generalized centre-to-centre method is proposed in this communication to deal with point objects with a Poisson distribution, a situation beyond the capacity of these methods and their modified versions, where the pre-deformation nearest neighbour points in the deformation state are a finite strain marker. This new method relies upon the probability mass function for the Poisson distribution, and adopts the maximum likelihood function method to solve for strain. The feasibility of the method is demonstrated by applying it to artificial data sets generated for a certain prescribed strain. Further analysis of these sets by use of the bootstrap method shows that the accuracy of strain estimate has a strong tendency to increase either with point number or with the inclusion of more pre-deformation nearest neighbours.

Meanwhile, an example of a deformed conglomerate, poorly sorted but well packed, is analysed, and the application gives rise to a similar strain estimate to the vector mean of the major axis directions of pebbles and the harmonic mean of their axial ratios. Both estimates give a retro-deformation map where the pebbles appear undeformed.

Mathematica Code for Image Analysis, Semi-automatic Parameter Extraction and Strain Analysis

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Geological strain analysis is a common task for structural geologists. This contribution presents software written on top of the Mathematica platform which allows for rapid semi-automatic strain analysis. The methods incorporated into the software are the Delaunay Triangulation Nearest Neighbour Method (DTNNM) and the Mean Radial Length method (MRL), which are based on the centre to centre method and Rf/Φ.

After an initial step of manual identification of strain markers, the software performs image analysis, parameter extraction and strain analysis using the shape and relative spatial positioning of markers. Bootstrap estimates of sampling errors are calculated and suitable graphical output is generated.

Quantifying strain distributions in ductile shear zones using quartz crystal preferred orientations, Karakoram Fault Zone, NW Himalaya

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Determination of quantitative strain distributions within orogen-scale ductile shear zones is of fundamental importance for understanding strain localisation processes and the macroscopic structure of fault zones. However, most crustal-scale shear zones lack sufficient strain markers. We show that in such circumstances, a suitable strain proxy can be provided by the intensity of quartz crystal preferred orientations (CPO), using the eigenvalue-derived Intensity parameter proposed by Lisle (1985). This method is widely applicable to quartz bearing rocks and may therefore provide near continuous strain profiles. Using this method, transects across the Karakoram fault zone, NW Himalaya, provide one of the first quantitative assessments of the strain distribution across such a large scale shear zone. Strain is distributed across multiple km-scale subparallel strands which cross-cut *c*. 16 Ma granitoids and separate less deformed lenses. The 'wet' quartz *c*-axes CPO lack crossed-girdle distributions but Y-maxima indicate deformation dominated by prism-*a* slip, suggesting temperatures of *c*. 500-550°C. Al-in-hornblende geobarometry on a cross-cut 17-18 Ma monzogranite gives 449±40 MPa corresponding to an emplacement depth of *c*. 17 km, thus providing a maximum depth constraint for the formation of the strain profiles. This is consistent with amphibole-plagioclase thermobarometry on *c*. 17 Ma migmatite restite equilibrated at 688±9°C and 522±34 MPa (*c*. 19 km depth), giving an apparent Miocene geothermal gradient of 35°C/km. These strain profiles provide an important insight into the distribution of deformation in the region between localised brittle deformation in the seismogenic upper crust and broadly distributed deformation in the partially molten mid-crust.

Strain analysis in dilatational shear zones, with examples from Marloes Sands, SW Wales

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New and existing methods for the analysis of finite strains in shear zones involving volume changes are reviewed. By assuming that the wall rocks are undeformed, the position gradients tensor can be determined from data derived from deformed passive markers with or without knowledge of the orientation of cleavage within the shear zone. The new methods are both algebraic and graphical and include those based on off-axis Mohr circles. If two non-parallel passive markers are present, the graphical method is a direct visual method for estimating components of displacement parallel and perpendicular to the shear zone boundary. This simple method has the advantage that it helps the user evaluate the quality of the data being used. The ideal markers are mutually perpendicular, whilst pairs of near-parallel markers place only loose constraints on the strain components. In the latter case, markers at high angle lead to poor estimates of the normal components of displacements; marker at a low angle to the shear zone boundary are not reliable for estimating the magnitudes of the shear-zone parallel components of movement. Application of these methods to deformed sandstones at Marloes Sands reveals important volume changes that would invalidate an approach that assumes simple shear.

Topographic evidence for continental plateaux growth mechanisms

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The Tibetan, Iranian and Andean plateaux result from plate convergence, and are first-order tectonic and geomorphic features of the continents. Their structure and elevation histories are debated, especially the possible roles of mantle lithosphere detachment and lower crustal flow. Plateau surfaces are above the regional elevation limit of larger (M >5) thrust earthquakes, requiring an additional cause of surface uplift to the brittle, localised thrusting of lower elevation regions. We use topographic swath profiles to show the different patterns of plateau growth. Several plateau margins (e.g. Qilian Shan, Longmen Shan, Bolivian/N. Chilean Andes) have slope values of ~1.5^{o} and a profile inflection at the elevation limit of larger thrust earthquakes, below a section with a lower slope value. The gentler gradient, higher elevation regions do not produce major thrust earthquakes. Instead, crustal thickening takes place via distributed, largely aseismic, thrusting and folding, with surface uplift via crustal isostasy. The dominant deformation mode for upper crustal thickening plausibly changes from brittle to ductile at the location of the elevation profile inflection. Thrusting is inhibited in the interior of each plateau because the gravitational potential energy is greater than at the plateau margins. Steepest margins (~3 to 3.5^{o} slope) occur where plateaux are bordered by strong basement (e.g. central Himalayas, Kunlun, Peruvian Andes, Alborz) and plateau interior elevations have reached their maximum value. Low regional slope (≤0.35^{o}) occurs where deformation propagates readily into the foreland (e.g. SE Tibet, eastern Zagros), but is not an unambiguous signature of lower crustal flow. Our results require re-evaluation of existing models of plateau evolution and surface uplift.

Morphotectonic study of Dushwan Uplift between Kerkuk and Qara-choq Anticlines using Remote Sensing Techniques

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The aim of this study is to demonstrate the morphotectonic evidences (drainage pattern, structural ridges deformation and spectral reflectance differences…etc) for Dushwan uplift. The study area is located in the Low Folded Zone at geographical coordinates (35º 45´ to 35º 55´) North and (43º 30´ to 44º 00´) East, surrounded by Kerkuk Anticline at the north and Qara-choq Anticline at the south.

Dushwan uplift has been determined in this study by the visual interpretation of the satellite images and the digital interpretation of the DEM and satellite images using softwares (ArcGIS and Global Mapper) for the study area.

The regional stress coming from the collision of the Arabian Plate with the Eurasian Plate still affecting the study area, as presented by the deformation of the southern structural ridges of Kerkuk Anticline and the whole Qara-choq structure and dividing the drainage pattern into two different directions from the centre of this uplift. In addition to the deformation of the eastern plunge of Bai hassan anticline. This uplift is shown by four sectional profile, three of them produced by Google earth instruments and the last produced by global mapper software.

Those morphotectonic evidences improves that the study area has been influenced by tectonic activity (Dushwan uplift) through two suggested procedures:-

1- Propagation of two synclines one of them existed between Kerkuk Anticline and Bai hassan Anticline and the other located between Qara-choq Anticline and Guwair Anticline with a north west- south east.
2- Tectonic uplift resulted by two regional faults extended adjacent to the Greater Zab and the Lower Zab with northeast- southwest trend.

Key words: Tectonic, Uplift, Remote sensing, Syncline

Kinematics of transpressional structures in an oblique subduction setting: Caribbean plate margin, offshore northern Colombia.

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The Bahia Basin is located in the NW corner of South America where a complex history of subduction, accretion and transpression is on-going since Cretaceous times. The Bahia Basin is located just offshore from major strike-slip fault systems that affect northern Colombia and lies behind the toe of the modern accretionary wedge, where the Caribbean Plate is being subducted obliquely beneath South America.

This study uses a high quality 3D-PSTM seismic volume, regional 2D seismic reflection lines, together with borehole data from one exploratory well drilled within the area of the 3D seismic volume. The mapping of the Upper Miocene Unconformity (UMU) highlights the presence of a young, deep, narrow basin trending NE-SW which is bounded to the NW by a major fault: the Bahia Fault. This fault shows an initial phase of normal displacement with later inversion along some segments. To understand the geological evolution between pre- and post- late Miocene times, structures below and above the unconformity were mapped on vertical sections, time-slices and using a variety of seismic attributes including spectral decomposition and coherency.

Structures below the UMU show high-density, low-displacement, domino-style normal faults. These faults form 3 groups within blocks that broadly correspond to the 3 fault segments that form the Bahia Fault. The boundary of each block is also marked by the presence of relay zones between each fault segment and small mud diapirs are found at boundaries of the central block. In the most southerly fault block, the main set of normal faults strikes NW-SE, orthogonal to the Bahia Fault. At the western end of the block there are a small group of NE-SW trending faults and there is a hint that fault orientations fan within the block. In the central block the faults strike between NNE-SSW and N-S. In the northern fault block the faults mainly oriented E-W and they have sigmoidal geometries at the fault tips indicating that they formed in a zone undergoing right-lateral shear. The change in orientation of the normal faults between the different blocks is explained as a possible result of vertical-axis block rotation linked to the opening of the young depocentre. Subsequently the Bahia Fault has been inverted and SW-NE trending folds have formed in rocks above the UMU as a result of the latest stage of shortening related to subduction at the Caribbean Plate margin.

The Bahia Fault occurs within a zone of distributed strike-slip deformation at the rear of the Miocene-Recent accretionary wedge and has been the locus of right-lateral transpression leading to clockwise rotation of blocks within its hangingwall and the opening of the deep Bahia Basin in Miocene to early Pliocene times. Such deformation is consistent with the strain partitioning that is both observed and predicted to occur at oblique convergent plate boundaries.

Evolution of Central Anatolian Basins; Unravelling subduction and collision history of Neotethys in Turkey: Preliminary results on Haymana Basin

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The Haymana Basin straddles the Izmir-Ankara-Erzincan Suture Zone (IAESZ) in the north and Intra-Tauride Suture Zone (ITSZ) in the south. These suture zones demarcate the former position of Neotethys Ocean in Turkey and are formed due to subduction of Neotethys Ocean and collision of Pontides of Eurasian affinity in the north and Taurides and Kırşehir Block of Gondwana affinity in the south. Haymana Basin is located in a very crucial position where IAESZ and ITSZ meets and comprises late Cretaceous to Middle Eocene possibly complete (but with local unconformities) infill that recorded subduction (fore-arc basin stage) to collision (foreland basin stage) history of the region.

This study is supported mainly by DARIUS Programme and aimed at unravelling the tectonostratigraphical development of the Haymana Basin and its tectonic position within the subduction of the Neotethys and collision history of the intervening continental blocks since the Late Cretaceous by means of biostratigraphical, magnetostratigraphical and thermo-chronological tools for precise dating, paleomagnetism for vertical axes rotations, fault slip data for kinematic evolution of the basin and creating balanced cross-sections to test and correct structural evolution of the basin . In addition to thick Neogene units, four Late Cretaceous to Paleogene key sequences have been determined in the basin. These sequences laterally and vertically grades into each other that makes deposition continuous from the Late Cretaceous to Eocene while local unconformities and frequent depocenter migration took place in response to south-vergent thrusting and related local uplift and subsidence. In order to determine the timing of these events and age span of the sequences precisely, 12 thermo-chronology and more than 2000 paleomagnetic samples have been collected from the basin and partly analyzed for thermo-chronological evolution, magnetostratigraphy and vertical axes rotations purposes. In addition to these, from 50 stations more than 2000 fault slip data have been collected for kinematic analyses and more than 400 stations bedding attitude data have been collected for cross-section studies .

Quantifying Barrovian metamorphism in the Danba Structural Culmination of eastern Tibet

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The Danba Structural Culmination is a tectonic window into the late Triassic to early Jurassic Songpan-Garzê Fold Belt of eastern Tibet, which exposes an oblique section through a complete Barrovian-type metamorphic sequence (Huang *et al.* 2003). Systematic analysis of a suite of metapelites from this locality has enabled a general study of Barrovian metamorphism, and provided new insight into the early thermotectonic history of the Tibetan plateau (Weller *et al.* 2013).

The suite was used to create a detailed petrographic framework, from which four samples ranging from staurolite to sillimanite grade were selected for thermobarometry and geochronology. Pseudosection analysis was applied to calculate pressure—temperature (*P—T*) path segments and determine peak conditions between staurolite grade at ~5.2 kbar and 580 ºC and sillimanite grade at ~6.0 kbar and 670 ºC. *In situ* U—Pb monazite geochronology reveals that staurolite-grade conditions were reached at 191.5 ± 2.4 Ma, kyanite-grade conditions were attained at 184.2 ± 1.5 Ma, and sillimanite-grade conditions continued until 179.4 ± 1.6 Ma.

Integration of the results has provided constraints on the evolution of metamorphism in the region, including a partial reconstruction of the regional metamorphic field gradient. Several key features of Barrovian metamorphism are documented, including nested *P—T* paths and a polychronic field gradient. In addition, several atypical features are noted, such as *P—T* path segments having similar slopes to the metamorphic field gradient, and T_{max} and P_{max} being reached simultaneously in some samples. These features are attributed to the effects of slow tectonic burial, which allows for thermal relaxation during compression. While nested, clockwise *P—T*—time loops provide a useful framework for Barrovian metamorphism (e.g. England & Richardson 1977), this study shows that the effects of slow burial can telescope this model in *P—T* space. Finally, the study demonstrates that eastern Tibet experienced a significant phase of crustal thickening during the Mesozoic, reinforcing the notion that the plateau may have a long history of uplift and growth.

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Hidden tectonics at mid-ocean ridges: insights from the Troodos ophiolite, Cyprus.

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Oceanic crust is created by seafloor spreading at mid-ocean ridges (MOR), which is accommodated by a combination of magmatism and tectonic stretching. Architecture of the oceanic crust is far more heterogeneous and segmented than the classic "layer cake" Penrose model, which cannot account for the varied nature of the crust in magma-poor environments.

It is now recognised that faulting plays an important role in spreading; but exactly how significant is the faulting? What role do sea-floor faults have on controlling lava accumulation? How can we assess the amount of tectonic stretching? Recent investigations of MOR show evidence for large offset normal faults or detachments that accommodate a significant fraction of the plate separation. Once thought of as rarities along the global spreading system, detachment faults are now considered to play an integral role in seafloor spreading at slow spreading ridges. Estimates of the proportion and extent of tectonic spreading however vary widely; some authors suggest as much as 50% of the Mid Atlantic Ridge is underlain by active detachment faults.

Amagmatic spreading structures may be actively accommodating extension even where they are not visible on the surface. However it is unclear how extensive the detachments are at depth. The lack of consensus is in part a consequence of the difficulty in documenting the extent of tectonic stretching and detachment faulting. Surveys of modern MOR reveal lava flows blanketing the seafloor obscuring the tectonic activity that must be occurring below the surface. Assessments of tectonic stretching based on surface morphology alone may be significantly underestimating tectonic extension. To see the hidden tectonic activity we must look to ophiolites where it is possible to examine the internal structure of the crust. The Troodos ophiolite, Cyprus, is believed to be a slow-spreading ridge analogue. Well preservation and exposed, it offers an excellent opportunity to examine the crustal architecture and fossilised spreading structures in multiple dimensions.

In this contribution we present field observations from the Troodos ophiolite. Our interdisciplinary approach utilises structural mapping, palaeomagnetism and geochemistry to investigate estimates of the extent and effects of detachment faulting within the ophiolite. We document significant extensional faulting and rotation within the crust above a detachment fault at the level of the sheeted dyke complex, yet show that the lavas at the surface are sub-horizontal and unaffected by the deformation beneath. Unconformities in the lava section demonstrate progressively greater rotations deeper in the extrusive pile. We show these rotations to be controlled by tectonic stretching and tilting of the underlying dykes rather than rotation by loading and/or subsidence within the lava pile.

Our results show that syn-tectonic volcanism fills half-graben on the seafloor such that minimal tectonic stretching is evident at the surface, but blankets tens of per cent tectonic extension at depth. We discuss the implications of these findings for modern slow-spreading mid-ocean ridge systems.

Old and new work on grain and phase boundaries

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Classical polarized light and universal-stage microscopy and the recently developed FIB technique, combined with TEM studies, provide information about the nature of grain and phase boundaries and their importance for physical properties of rocks and deformation and metamorphism. In metamorphic and syntectonic magmatic rocks sutured grain boundaries are common, as a result of strain-induced grain-boundary migration and stabilisation of facets in preferred crystallographic orientations (Fig.1). Although these orientations and the geometry of the sutured boundaries are affected by various parameters, such as deformation intensity, they mainly reflect temperature at the end of deformation and, under certain conditions, allow to relate deformation events to the temperature development. In addition, the crystallographic control on grain-boundary facets governs grain coarsening after deformation, which may also serve as a fabric-related geothermometer.

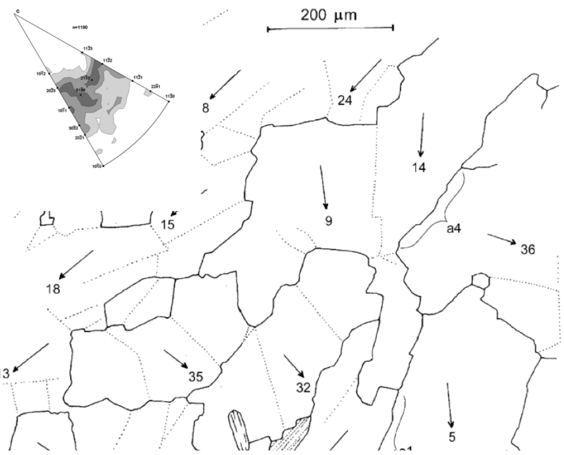

Fig. 1: Recrystallized quartz grains with c-axis orientations (arrows) and facetted boundaries. Circle segment: crystallographic orientations of facets. After Kruhl & Peternell (2002) and Kuntcheva et al. (2006).

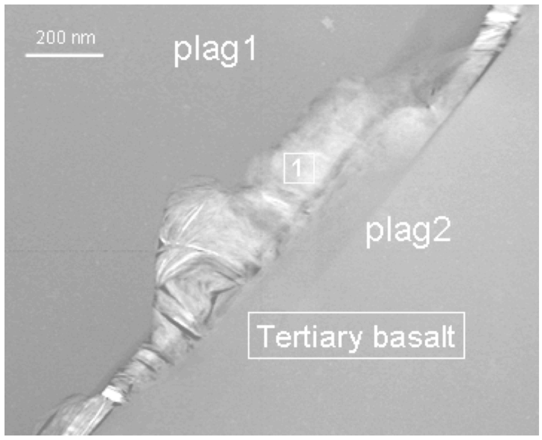

Fig. 2: TEM image of an open plagioclase grain boundary and cavity, filled with chlorite. Kruhl et al. (2013) and unpublished data.

Transmission electron microscopy shows that grain and phase boundaries of various rock-forming minerals (calcite, quartz, plagioclase, K-feldspar, amphibole, pyroxene) from magmatic and metamorphic rocks (basalt, syenite, quartzite, marble, metagabbro, eclogite) are partially open up to several hundred nanometres and form a connected network that serves as pathway for fluids. The data are in agreement with cooling-related anisotropic volume reduction below the diffusion thresholds of the different minerals, which is not balanced by decompression-induced anisotropic volume expansion. The voids are partially filled with newly grown quartz, biotite, chlorite or amphibole (Fig.2), indicating the presence of open grain and phase boundaries already at deeper crustal levels, with consequences for porosity, fluid flow, reactivity and mechanical behaviour of the rocks.

Kruhl, J.H., Peternell, M., 2002. J. Struct. Geol. 24, 1125-1137. Kuntcheva, B.T., Kruhl, J.H., Kunze, K., 2006. Tectonophysics 421, 331-346. Kruhl, J.H., Wirth, R., Morales, L.F.G., 2013. J. Geoph. Res. Solid Earth 118, 1-11.

Cavitation bands and fluid flow in fine-grained ultramylonites deforming by grain size sensitive creep in the continental lower crust

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Shear zones channelize fluid flow in the Earth's crust. A number of mechanisms were suggested to control fluid migration pathways in upper- and midcrustal shear zones, amongst them creep cavitation, which is well-known from deforming metals and ceramics. Deep crustal fluid migration is hardly constrained by any observations, and so it remains unclear how fluids are channelized and distributed in an actively deforming lower crustal shear zone.

This study investigates the deformation mechanisms, fluid-rock interaction and development of porosity in a mangerite ultramylonite from Lofoten, northern Norway. The synkinematic mineral assemblage consists of plagioclase, K-feldspar, hornblende, quartz, calcite and biotite, and yields P, T conditions of deformation of 700-730° C, 0.65-0.8 GPa. Mass-balance calculations indicate (1) a volume increase of 2.3%, and (2) fluid infiltration during the protolith-ultramylonite transformation.

Microstructural observations and EBSD analysis are consistent with diffusion creep as the dominant deformation mechanism in the ultramylonite. The microstructure shows extensive evidence of synkinematic nucleation of new phases in dilatant sites resulting from the concomitant operation of grain boundary sliding and cavitation during grain-size sensitive creep. EBSD maps show the occurrence of isolated quartz grains along C' shear bands in feldspathic layers. Quartz does not show a crystallographic preferred orientation in these bands, suggesting that it precipitated in cavities. The occurrence of such quartz bands is consistent with the coalescence of individual pores originally formed at dilatant sites resulting from the operation of grain boundary sliding. Opening of pores implies local dilatancy. Positive volume change accompanied by fluid infiltration, as inferred from the mass balance calculations, is consistent with the precipitation of new phases in pores from intragranular fluids.

We used synchrotron X-ray microtomography to analyse shape and distribution of pores in two feldspathic layers. The pores (6-30 mm in diameter) are preferentially distributed along C' shear bands, lending support to our interpretation of precipitation of quartz in cavitation bands with a C' orientation.

In summary, this study presents clear evidence that porosity can be organised in shear bands as a consequence of creep cavitation during grain-size sensitive flow in lower crustal shear zones. It is likely that new phases precipitate from intragranular fluid in such cavitation bands, which may control deep crustal fluid flow.

Superplastic flow lubricates carbonate faults during earthquake slip

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The causes and grain-scale expression of dynamic weakening along faults at seismic slip rates (v ~ 1m/s) remain enigmatic. We present mechanical data and microstructural (SEM, TEM) observations from displacement-controlled friction experiments performed in a rotary shear apparatus on calcite gouges at seismic slip rates and normal stresses up to 18MPa. Friction initially increases to peak values (m=0.75) before decaying to lower steady-state values (m=0.2), with a typical slip distance d of ~20cm. Up to 80% of the peak friction is recovered during deceleration to arrest.

Microstructural observations on samples deformed up to the attainment of peak friction (m=0.75) show the development of a localised, porous slip zone, <150 mm thick, with multiple striated slip surfaces coated by sub-rounded nano-grains. Although seismic slip rates (v > 0.7 m/s) are attained, no dynamic weakening is observed. Once the steady-state stage is established (m=0.2), a 50 mm thick, low porosity cohesive slip zone develops composed of juxtaposed domains of nano-grains bounded by multiple, striated slip surfaces. The sub-micron domains comprise interlocking calcite grains with distributed sub-grains < 20nm in diameter, with straight, polygonal boundaries displaying 120° triple junctions. Textural evidence for dynamic recrystallization by dislocation creep is absent and slip zone internal architecture is not obliterated by the polygonal fabric development, i.e. no evidence of annealing.

We propose that cataclastic reduction down to nanoscale grainsizes and intense frictional heating due to shear localisation may have activated transient diffusion-dominated grain boundary sliding (GBS) mechanisms leading to superplastic flow and dynamic weakening in the slip zone. Using constraints from the experimental conditions (strain rate, T) and microstructural observations (d), we calculated the predicted strengths using a range of constitutive flow laws for grainsize-sensitive and -insensitive mechanisms. At the very high strain rates achieved during the experiments, the flow law for superplastic flow is the only one that predicts the measured strengths. The re-strengthening observed during the decelerating shearing phase is explained by falling temperatures "switching off" the nano-scale GBS leading to a return to frictional sliding and cataclasis.

Field and experimental investigation of the seismic potential of mechanically heterogeneous thrusts

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We studied three large-displacement (5-10 km), exhumed (≈2 km depth) thrust faults from the Northern Apennines (Central Italy), in the field and in the lab. We addressed the influence of different lithologies on fault zone structure and deformation mechanisms.

Macroscopic and microstructural evidence suggest strong differences in the mechanical strength and slip behaviour (seismic vs. non-seismic) of the different fault zones: we observe a full spectrum of fault zone architecture from localized brittle faulting to ductile shear zones that depend on the faulted lithology. Brittle shear zones found in massive limestones present abundant cataclasites, ultractaclasites, fault mirrors and decarbonation structures (evidence of seismic slip). On the other hand, ductile shear zones, which tend to develop in marly formations, are characterized by S-CC' tectonites due to pressure solution and frictional sliding along phyllosilicate lamellae.

To test these observations we carried out experiments on these natural fault rocks. We sheared both intact wafers and powdered fault materials applying low (10 MPa) and in-situ (53 MPa) normal stress under water-saturated conditions. We used velocity steps (1 to 300 μm/s) and slide-hold-slide (3-1000 s holds) to assess the frictional stability and healing behaviour of our rocks.

Mechanical results quantitatively support the idea of mechanically heterogeneous Apennines fault patches as inferred from field and microstructural observations.

The study of these structures has important implications for our understanding of fault characteristics in carbonates and seismogenic potential in Italy and other parts of the world.

Day 3

Wednesday 8th January, 2014

Stress sensitivity of permeability in tight rocks

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Permeability is a petrophysical property that is of particular importance to reservoir engineering but also to the expulsion of fluids from rocks undergoing compaction and low-grade metamorphism, such as in thrust wedges and accretionary complexes. The time taken to dissipate periods of high pore pressure in tight rocks may favour easy slip and strongly impact upon seismogenesis. Permeability may be particularly sensitive to rock anisotropy but also to the effective stress state. Increase in effective mean stress or increase in sub-yield differential stress is expected to decrease permeabilility, although differential stresses sufficiently high to open microcracks is expected to increase permeability.

Measurement of very low permeabilities has traditionally been done using the pulse transient decay method but the oscillating pore pressure method is more resistant the effects of small temperature variations and to small pore fluid leakages. We have used this method to measure permeabilities of mudstones as a function of orientation with respect to layering, effective hydrostatic stress and sub-yield differential stress, primarily in the context of behaviour of gas reservoirs but also recognizing the more general implications.

Most mudstone specimens suitable for permeability measurements must be taken from borehole samples or from near-surface sites which are mostly under water, to prevent cracking by shrinkage during drying. Our samples were of Whitby (Jurassic) mudstone taken from the intertidal zone at Runswick bay, Yorkshire, a Jurassic shale from a borehole depth of 3.5 km, and from 2 borehole samples of Barnett shale (Texas). They were all dried to constant weight at 60 ^{o}C, although all were smectite-free. Argon gas permeability measurements were made at room temperature at confining pressures up to 70 MPa effective confining pressure, corresponding to about 3 km burial depth, at constant pore pressure of 25 MPa.

During initial effective pressurization, permeability parallel to layering falls rapidly from about 10^{-17} m^2 by about 2.5 orders of magnitude, after which successive decreasing then increasing pressure cycles produce a permeability that varies by a factor of ~10 over the effective pressure range used. All this pressure cycling is in the elastic behaviour range, and it is inferred that the first pressure cycle 'repairs' the greater part of the crack/void opening that occurred as a result of uplift from depth and sampling. Thus the reproducible behaviour during pressure cycling corresponds to the intrinsic 'at-depth' behaviour. The same pattern was observed for measurements across the layering (but with permeability lower by x100) and for the different mudstone types, and may be a characteristic response.

The obvious application of these results is to the performance of shale gas reservoirs. As pore pressure is drawn down on either side of a hydrofrac during production, permeability decreases and productivity falls off more rapidly than would be predicted using a constant permeability model.

Grain Growth in Halite

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The grain growth kinetics of halite have been experimentally investigated by hot-isostatic pressing reagent grade halite powder (99.5 %+NaCl) at 200 MPa confining pressure and different temperatures (330-600 ^{o}C) for durations ranging from 5 s to 120 days. The initial particle size of the halite was the 38-125 μm sieve fraction. During the initial stages of hot-pressing the halite recrystallized to a foam texture. Some porosity remained after recrystallization, the size and distribution of which appears to impact significantly on grain growth.

The grain size data are well described by the normal grain growth equation:

$$d^{1/n}-d_0^{1/n}=k_0(t-t_0)exp(-H/RT)$$

where d is the final grain size, d_0 is grain size at t_0, the time when the initial phase of recrystallization is complete, t is the duration of the experiment, n is the growth exponent (n = 0.25), k_0 is a constant (k_0 = 6.9807×10^{10} $\mu m^{1/n} s^{-1}$), H is the activation enthalpy (H = 120 kJmol), R is the gas constant and T is temperature. The growth exponent suggests that growth is controlled by surface diffusion around pore boundaries, while the calculated activation enthalpy agrees well with that for the surface diffusion of Cl^- ions around halite grains.

Abnormal grain growth is observed in some experiments conducted at temperatures above 400 °C. In order to attempt to investigate the influence of porosity on the development of abnormal grain growth, detailed microstructural analysis of the grain boundary porosity Zener parameter (pore diameter/pore volume fraction) has taken place using a low vacuum SEM. Results have shown that there is variability in pore volume fraction and diameter within individual samples thus highlighting the sensitivity of halite grain growth kinetics to the presence of grain boundary porosity. Of the two terms in the Zener parameter, porosity volume fraction appears to be the dominant factor in influencing the grain growth kinetics of halite.

The application of 4D synchrotron x-ray tomography in rock mechanics and structural geology

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We develop our understanding of rock deformational processes mostly by interpreting finite structures, usually in 2-dimensional sections, inferring what the evolution of the structures could have looked like. In field studies, these inferences are often backed by space-for-time assumptions, while in experimental geosciences post-mortem analyses are usually informed by indirect measurements of relevant mechanical parameters during the experiment. Few approaches, such as experiments in see-through deformation rigs, can document deformational processes on the granular- or even lattice scale in real time but even these are essentially confined to two dimensions. 4D synchrotron x-ray tomography promises to change this radically and bears the potential to revolutionize our approach to experimental rock mechanics and possibly even our understanding of some rock deformation processes.

Over the last years, synchrotron x-ray microtomography has become a widely available tool for non-invasive imaging of rock microfabrics. Current setups allow the acquisition of high-quality datasets in a matter of seconds. The brilliance of Synchrotron radiation and the accessible energy bandwidth even allows imaging through metal containers. State of the art x-ray transparent experimental vessels that make use of this capability can simulate conditions of fluid-rock interaction in most geological reservoirs. The next generations of x-ray transparent vessels, which will be ready for use within twelve months, will allow rock deformation experiments at synchrotron beam lines at greenschist facies conditions. The development of experimental vessels will likely match the anticipated upgrades at many synchrotron microtomography beamlines over the next years, promising exciting times ahead.

In this presentation I will use results from a series of recent 4D synchrotron x-ray microtomography experiments on dynamic porosity and fluid-rock interaction to outline the capabilities of the technique. I will describe down-stream data processing and analysis of extremely large 4D data and sketch our strategies to meet the challenges that come with these. Finally, I will review current and future capabilities at the leading synchrotron microtomography beamlines and our efforts in the design of experimental vessels that match these capabilities.

Mechanical anisotropy, strain localization, and crustal rheology

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Crustal rheology is commonly approximated by a strength envelope based on laboratory flow laws. For the viscous crust, such plots are generally made assuming homogeneous composition and strain rate. Consider, however, the observation that exhumed medium to high grade metamorphic terrains, representative of the viscous mid- to lower crust, preserve heterogeneous rock assemblages with a number of fabric elements. Within such rocks, neither composition, nor recorded strain, are homogeneous.

The Antarctic Maud Belt, which formed during Grenvillian, and later Pan-Africa, collision between Africa and Antarctica, and developed at amphibolite facies conditions, contains numerous low angle, reverse shear sense, viscous shear zones. These developed within a rock assemblage comprising metapelite, metapsammite, and various felsic orthogneisses. Although some smaller shear zones are present within orthogneisses, the major shear zones occur within metapelitic layers, and are characterized by relatively high proportions (> 20 %) of phyllosilicates. Here, composition, and particularly phyllosilicate content, was a critical control on strain distribution.

The Kuckaus Mylonite Zone, southern Namibia, developed at retrograde, amphibolite to greenschist facies conditions, within quartzofeldspathic rocks that had previously experienced granulite facies metamorphism. This subvertical, strike-slip shear zone is characterized by heterogeneously developed fabrics, which reflect along- and across-strike variability in strain, within rocks of relatively homogeneous composition. High strain zones, within which ultramylonites have developed, are either at the edge of almost unstrained granite bodies, or within rocks that contained a pre-existing, steep fabric defined by interconnected biotite layers.

These and other examples show that in exhumed rock assemblages, even where composition is relatively homogeneous, the presence of rheological heterogeneity causes a heterogeneous distribution of strain. This strain distribution reflects a heterogeneous distribution also in strain rate, where higher strain rates can be expected along weaker zones. In actively deforming regions, therefore, one may expect the presence of shear zones that form within weaker materials or exploit pre-existing weaknesses (such as faults, shear zones, or foliations in appropriate orientations). The presence of weak zones has a number of implications, such as crustal strengths lower that those predicted by most crustal strength curves, seismic activity extending deeper than predicted, along high strain rate zones, and significant heterogeneity in crustal rheology within actively deforming regions.

Behaviour of isolated elliptical inclusions in 2D viscous flow

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Reasonably isolated inclusions, such as clasts in some conglomerates or ooids in some limestones, have been used to determine finite strain in rocks under the assumption that they behave as passive markers. However, considering the different (and often variable) composition relative to the matrix, this can never be strictly true and even small rheological contrasts can markedly affect the results. At the other end of the spectrum, particles assumed to be rigid (e.g., porphyroclasts in mylonitic rocks) have been used to determine the sense of shear and to estimate the vorticity (so-called "kinematic vorticity analysis"). In these studies, it is invariably assumed that the inclusion is coherently bonded to the matrix, a necessary assumption in the derivation of the applied analytical solutions. The analytical solutions predict that for simple shear or transpression, any stable orientation of the long axis of an elliptical inclusion will be parallel to or, in the case of transpression, at a small synthetic angle to the shear plane. However, natural examples of "sigma clasts" invariably show a preferred orientation of the long axis at an antithetic angle, back-rotated relative to the shear plane (Fig. 1).

Fig. 1. Calcite sigma clast in dextral shear

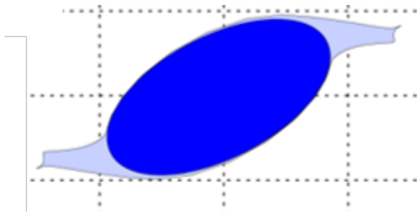

Fig. 2. FEM model of clast at $\gamma = 3$

This has been explained by confined flow, transtensional shear, the effect of adjacent particles, strain localization (e.g., on shear bands or C' structures), or slipping, incoherent or weakly rimmed boundaries to the inclusion. In this talk, a summary is presented of the behaviour of isolated deformable and rigid inclusions with both coherent and rimmed weak boundaries, for both linear and power-law viscous rheology. It is shown that in 2D the problem can be reduced to the behaviour of a passive line, scaled in terms of the viscosity ratio and axial ratio. This is strictly true for linear viscosity and still a good approximation for power-law viscosity. The observed natural behaviour of populations of stiff particles can be reproduced by models with incoherent weak rims around the inclusions, corresponding to finer grained mantles of recrystallized material around porphyroclasts. This analysis is based on an assumed elliptical and coaxial rim, but finite-element models to high shear strain show that the rotational and stretching behaviour is not fundamentally changed when the rims can also deform into more complex shapes (e.g., Fig. 2). The analysis demonstrates that the overall behaviour is controlled by a range of parameters and especially by the thickness and relative viscosity of the rim, so that there is not a direct and simple one-to-one relationship with the kinematic vorticity number. Unfortunately, kinematic vorticity analysis in shear zones using the orientation and axial ratio of stiff particles is therefore not feasible.

UK Geoparks and opportunities for collaboration with academic communities

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The Geopark concept grew from an idea at the turn of the millennium; a vision of four European territories working in partnership, that geological heritage should be valued, protected, and above all used sustainably to benefit local communities. In world where the climate is changing, resources are dwindling and communities are struggling to be communities in a real sense the time was ripe for such an idea. Four Geoparks signed a convention on Lesvos in June 2000 declaring the creation of the European Geoparks Network. Four years later in 2004 a Global Geoparks Network supported by UNESCO was born. In 2013 the Global Geoparks welcomed their 100th member.

One hundred territories around the world are now actively using their outstanding geological heritage to underpin the sustainable development of their regions in a bottom-up approach, primarily (though not exclusively) through education and tourism. Geoparks take a holistic attitude to interpretation, highlighting the close links between geodiversity and cultural and natural heritage. They raise awareness of key issues facing society in the context of the dynamic planet we live on and they seek to conserve the natural environment.

There are currently seven Global Geoparks in the UK : Geopark Shetland and North West Highlands Geopark in Scotland, North Pennines AONB and English Riviera Geopark in England, Fforest Fawr Geopark and Geo-Mon Geopark in Wales and Marble Arch Caves Geopark, which crossed the border between Northern Ireland and the Republic of Ireland.

This paper will demonstrate the potential for a closer linkage between the seven UK Geoparks and academic communities. An overview of the structural geology in each UK Geopark will be given, highlighting areas of research interest. Suggestions for engagement through field trips and collaborative projects will be outlined, using the 2013 visit of members of the Tectonic Studies Group to Shetland as a case study.

More information about the UK Geoparks can be accessed via http://www.shetlandamenity.org/uk-geoparks

The structural evolution of the Orcadian Basin, NE Scotland: multiple phases of regional rifting, reactivation and local inversion

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The onshore Devonian sedimentary rocks of the Orcadian basin host significant amounts of fracturing, faulting and some localized folding. Here we present a new study based on field and microstructural analysis of the structures found within the Devonian cover sequences and their underlying Precambrian basement rocks in Scotland and Orkney. Three main groups of structures have been identified based on orientation, kinematics and infill.

Group 1 faults trend ENE-WSW, N-S and NW-SE and display predominantly sinistral strike-slip to dip-slip extensional movements. They form the dominant structures in the eastern part of the northern coastal section in Caithness, and to a lesser extent Orkney, and are likely related to E-W extension during regional sinistral transtension along the Great Glen Fault Zone (GGFZ) during the Devonian. Gouges/breccias associated with these faults display little or no mineralization or veining.

Group 2 structures are closely associated systems of metre- to kilometre-scale N-S trending folds and thrusts related to a highly heterogenous regional inversion event recognized locally throughout the field area, but especially on Orkney. Once again, fault rocks associated with these structures display little or no mineralization or veining. The inversion reflects E-W shortening with local reactivation of pre-existing Devonian normal faults linked to regional dextral reactivation of the GGFZ. Existing geological constraints suggest a late-Carboniferous or early Permian age of inversion.

Group 3 structures are dextral oblique NE-SW trending faults and sinistral E-W trending faults with widespread syn-deformational carbonate mineralisation (± pyrite and bitumen) both along faults and in associated mineral veins. Stress-inversion analyses consistently point to NW-SE regional extension during this event. In a few localities (e.g. Dunnet Head, Scarfskerry, E. Scapa Fault) strike-slip inversion events have occurred at this time leading to localized folding during reactivation of pre-existing Devonian faults. Crucially, these later folds are synchronous with carbonate and associated mineralisation events unlike the Group 1 and 2 fold structures which are consistently cross-cut by these veins.

The pyrites associated with the Group 3 structures are commonly enriched in rhenium (^{187}Re) (ppb) which decays to Osmium (^{187}Os). Re-Os dating of syn-deformational pyrite was carried out at the Total Laboratory for Source Rock Geochronology and Geochemistry at Durham University. Isotopic analysis showed that there was no appreciable common osmium present in the sulphides at the time of mineralization allowing us to derive model ages for the faulting. This indicates that the pyrite-bearing fracture systems formed at 267.5 ±3.4 Ma (mid-Permian). The Group 3 structures are likely related to intrusion of the Orkney Dyke swarm(249-268Ma and to the rifting that formed the offshore West Orkney Basin located to the north and west of the older Orcadian Basin.

Structural Inheritance: Effects on the early evolution of the Barmer Basin rift

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Structural inheritance has long been known to affect the geometries of structures generated during the early stages of rifting. However, few rift-evolutionary models account for such inherited structural involvement. Here we describe how structural inheritance influenced the early-stage evolution of the Barmer Basin, India, generating unique and irregular basin margin accommodation structures that do not fit with classical accommodation or transfer zone models.

Working across two scales of investigation, we combine targeted field mapping with sub-surface seismic interpretation to construct a structural model that focuses on the early basin fill local to the field area, and shows how the initial rifting along the basin margin was accommodated. We find evidence for two episodes of non-coaxial extension, with structural inheritance evident during both, the effects of which varied.

Subsurface interpretations show that a significant rift-oblique structure, active during early extension, was incorporated into the eastern basin margin fault system and facilitated displacement transfer between right-stepping fault systems to its north and south. Displacement transfer was achieved through fault splays and block rotations. As such, the structural geometries and location of early depocentres do not conform to that predicted by classical accommodation and transfer zone models.

Our results show how pre-existing crustal structures can affect basin evolution during the early stages of rifting, and may persist throughout the evolution of the rift. The structural relationships described do not fit 'classical' accommodation or transfer zone models and, as a result, early depocentre location and linkage in the Barmer Basin deviates from accepted models of depocentre evolution. It follows that understanding the involvement of such structures during early-stage rifting may be important in understanding structural complications and prediction of early basin sedimentary fills, and thus source and reservoir facies distribution, in many continental rifts.

Linking basin tectonics, evaporite facies variations and their impact on subsequent deformation: insights from the Messinian

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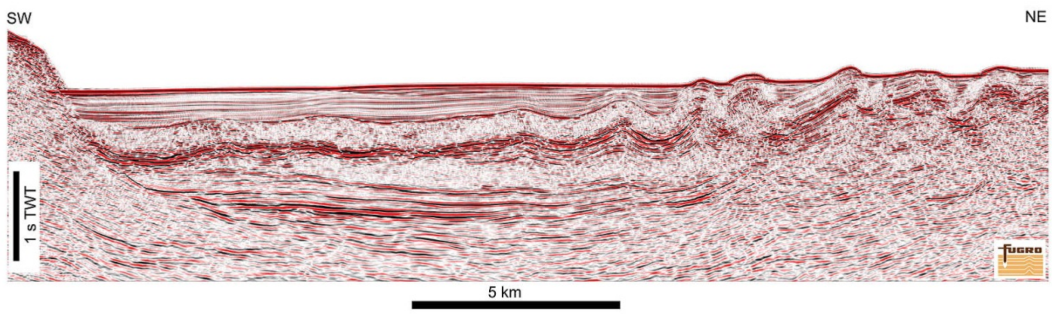
With improvements in seismic imaging, it is increasingly evident that original stratigraphic variations in evaporite formations can play important roles in their deformation. Critical in this regard is the relative abundance of halite, together with other high-solubility salts, and the less soluble calcium sulphates and carbonates. Our aim is to demonstrate the length-scale of variations in evaporite stratigraphies deposited in thrust-top basins and how these variations have controlled subsequent deformation of these basins. We use Messinian examples that integrate outcrop observations with extensive subsurface data from Sicily to provide new structural interpretations and apply these insights to interpret seismic data (in the absence of well control) from the nearby Ionian Sea. These Messinian basins are excellent sites for studying lateral variations in evaporite successions and their subsequent deformation. Two areas of the Sicilian thrust system are used here, linked to three major mine areas (Realmonte, on the south coast; Corvillo and Mandre in the centre of the island). Thrust-top mini-basins control fractionation of carbonate-evaporite facies that then continue to influence post Messinian deformation. Gypsum and carbonate units develop broad single-layer buckle-fold trains, wavelengths reflecting layer thickness. The development of deformation appears limited by bending resistance at fold hinges – which can be overcome by syn-tectonic erosion. In contrast, the thick halite deposits that accumulated in growth synclines have deformed with short-wavelength folds and distributed strain. These structures can display rapid lateral variations over length scales of a few hundred metres. Similar structural styles – with buckle fold trains passing laterally into more homogeneously shortened, short wave-length folding - are evident on seismic data from the buried Messinian interval beneath the Ionian sea. Using the Sicilian outcrop as analogues, the structural styles for the Ionian may be used to infer evaporite type in these subsurface examples.



Deformed Messinian evaporites, floor of western Ionian Sea. Image courtesy of the Virtual Seismic Atlas (www.seismicatlas.org) and Fugro (now CGG).

Basin structure and evolution within the Gulf of Corinth rift using a refined chronostratigraphic model from integrated geophysical data

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The Gulf of Corinth is a classic young active rift (<5 Ma) in its initial stages of development. An abundance of marine geophysical data collected over the past two decades makes it an ideal case study for investigating early rift evolution. Using an integrated network of numerous offshore seismic reflection datasets, totalling ~5000 km of seismic profiles that cover the entirety of the rift, we present a refined chronstratigraphic model of the past ~1-2 Myr of syn-rift sedimentation within the developing Corinth basin. The new chronostratigraphic model reconciles previous stratigraphic interpretations from different areas of the Gulf and provides the temporal framework for investigating the basin evolution and fault network development of the entire offshore rift.

Our chronostratigraphic model divides the rift stratigraphy into three units separated by unconformities. These include lower and middle units (pre- ~550 ka) that are thought to represent earlier non-marine sedimentation and an upper unit (post- ~550 ka) which can be divided into alternating marine-lacustrine deposits. The upper and middle units are separated by a basin wide unconformity that marks the onset of the first marine transgression into the basin. We divide the upper unit into six conformable packages that are identified throughout the rift and can be correlated with 100 kyr glacio-eustatic cycles. Our results indicate that chronostratigraphic models based on stratigraphy in the western Gulf are coherent with those from the central Gulf. Furthermore our chronostratigraphic model correlates well with highstand-lowstand sedimentary structures seen in the Alkyonides basin (eastern Gulf).

The rift basin geometry has a complex history and varies spatially along strike of the rift. Using isochore maps, for sediments both before and after the ~550 kyr unconformity as well for each 100 kyr glacio-eustatic cycle, we illustrate in detail the development of numerous depocentres throughout the rift. In the western rift we identify an unconformity within the upper unit at ~340 kyr which coincides with a change in sediment deposition within the central Gulf. This is related to a change in fault dominance from S-dipping faults to N-dipping faults at this time. To fully understand these structural developments within the rift we combine the refined chronostratigraphic model with a detailed fault network, allowing us to investigate the organization of faulting and displacement distribution within the rift basin for each 100 kyr interval. We focus on the accumulation of displacement along strike of the fault network and understanding changes in fault polarity, both spatially and temporally. This will allow us to determine the relative timings of key rifting events within the modern rift over the past ~1-2 Myr.

A mathematical envelope to assess the distribution of BSRs on tectonically active margins

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A 3D seismic volume from the Nankai Trough accretionary wedge (SE Japan) has been used at Cardiff to evaluate the subsurface distribution of gas hydrates as a function of tectonic activity, variable heat flow patterns and the presence of sub-surface fluid conduits. In this talk we will show how eleven equations modified for depth, pressure and temperature, were modelled in 3D and compared with the distribution of Bottom-Simulating Reflections (BSRs) offshore Nankai.

Our results show that the equations produce overlapping - and thus potentially consistent - predictions for the distribution of BSRs, leading us to propose the concept of a 'BSR Stability Envelope' as a method to quantify the sub-surface distribution of gas hydrates on continental margins. The analysis of a ratio (R) between shallow and deep BSRs of seven sub-envelopes, which are defined by BSR stability equations, indicates local gas hydrate equilibrium conditions. Values of $R<1$ relate to cooler regions, whereas when $R>1$ the majority of BSRs are located in warmer structural traps.

We will show that the method can be important to recognize any divergence between observed and theoretical depths of occurrence of BSRs on 3D or 4D (time-lapse) seismic volumes. In the specific case of the Nankai Trough, our results point out for equilibrium conditions in BSRs located away from the Megasplay Fault Zone and major thrust anticlines, i.e. away from main fluid flow paths and regions of tectonic uplift. This talk will specifically demonstrate the applicability of our method to:

a) The recognition of subsurface fluid conduits,

b) The recognition of tectonically active structures on continental margins, as the depth of occurrence of BSRs significantly changes within active thrust anticlines and eroded hanging-wall blocks of major thrust faults.

Structural controls on the geometry of the Tuzon gold deposit, Southern Liberia

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The Tuzon gold deposit is located in southwest Liberia. Mineralisation is hosted by granulite-facies, orthopyroxene gneiss and predominantly localised within a single layer, sub-parallel to the contact between the orthopyroxene gneiss and adjacent feldspar-biotite gneiss. Gold is inferred to have been introduced into the system prior to peak metamorphism and then remobilised into a variety of textural sites during retrograde metamorphism.

Tuzon is located 1km from the crustal-scale Dugbe Shear Zone. However, drill core logging indicates that deformation at the project-scale is dominated by multiple phases of folding, with only local shearing. Structural logging of drill core identified 3 major folding phases:

- F1 is an early, isoclinal folding phase that causes local thickening of mineralisation but does not significantly affect the macro-scale geometry of the deposit.
- F2 is a tight folding phase that refolds mineralisation. This results in two distinct mineralised layers in the central part of the deposit and a thickened, mineralised hinge in the north of the deposit.
- F3 is a close folding phase with a moderately, southeast-dipping axial plane and shallowly, south-plunging fold axis. It is the dominant control on the macro-scale geometry of the deposit.

The F3 folding phase is associated with significant transposition and the axial planar foliation is the dominant structural fabric in the project area. Definition and modelling of the earlier folding phases relied on combining small-scale fold observations and measurements in drill core with lithological and mineralisation modelling in 2D and 3D.

The resulting fold shape was too complex to allow resource estimation in standard software packages. Instead, a folded block model was constructed using GoCAD software to allow the data to be unfolded and assessed as a flat planar body. This process provided significant improvements to variogram ranges and robustness. However, variogram range parallel to the fold axis was still larger than in the profile plane of the fold, even after unfolding. This is attributed to small-scale folding and transposition that could not be accurately modelled at the deposit scale.

Poster Presentations

Day 1

Monday 6th January, 2014

Geometry and scaling relationships of deformation band lozenges and fault lenses

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Deformation bands can affect fluid flow in hydrocarbon reservoirs and therefore, understanding the geometrical attributes of individual bands and their scaling relationships is a critical step in quantifying their connectivity. We present a geometrical study of deformation band lozenges (rock volumes that are contained between deformation bands) and ladder fractures that developed in faulted sandstones from the Moray Firth (Scotland) and southeastern Utah (USA). We investigate the statistical trends among different deformation band lozenge and fault lens datasets and explore their potential correlation to other attributes of the fracture pattern and the petrophysical properties.

The aspect ratios of lozenges show an oblate-shaped geometry. The length-thickness scaling relationships of lozenges have different statistical trends as for lenses. The scaling relationships show a break in slope between lozenges bounded by deformation bands and lenses bounded by slip surfaces in the fault core. This break marks the boundary between the lozenge domain and lens domain. The variation in slopes is likely due to the transition from one deformation mechanism to another. i.e. strain hardening (deformation banding) versus strain softening (faulting). In addition, we quantify the geometrical attributes of lozenges and lenses in faulted sandstone, using sliced rock samples as input for 3D geometrical models. The geometry of ladders is antithetic and displays a 45^{o} obliquity to the orientation of deformation bands. We thus propose a Riedel shear model that accommodates conjugate sets of ladders between sub-parallel sets of deformation bands. The integration of geometrical modelling with an understanding of scaling relationships can help to make better predictions of fractures and fault properties in subsurface reservoirs.

A review of polygonal fault systems and their hydrocarbon prospects

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Polygonal faults are arrays of layer bound extensional (normal) faults within mainly fine-grained stratigraphic sub-horizontal intervals. These faults trend diversely and intersect variably forming polygonal geometries in plan. High resolution 2D- and 3D seismic data reveal polygonal faults worldwide in more than hundred basins. The faults are either planar or are gently listric with 30 to 70° dip. Individual fault segments are 80-1400 m long, 100-500 m spaced and of 10-100 m throw. These faults form by compaction-driven fluid expulsion at shallow depth with increase in vertical effective stress. Since polygonal faults develop in a uniform stress field, neither Anderson's- nor Hafner's mechanisms apply. Instead, the proposed mechanisms include density inversion, syneresis, contraction driven shear failure, differential compaction on diagenetic reaction boundary, and low coefficient of residual friction. Polygonal fault systems enhance directional hydraulic conductivity within impermeable layers. Sedimentary loading driven overpressure pushes the fluid. Linear Positive High Amplitude Anomalies above polygonal fault systems connote vertical migration of pore fluids/hydrocarbons/gas hydrates/thermogenic fluids/fresh water. Focused vertical migration of fluids yields triple junctions. Syn-sedimentary deformation and sand intrusion by liquefaction enhance reservoir connectivity. Underestimating these constraints may undermine reservoir potential. Fluid-flow features, such as gas chimneys, developed above the polygonal fault systems indicate hydrocarbon rich source/reservoir rocks. Active fault systems reach modern sea-floor forming pockmarks. Moscardelli et al. (2012) suggested polygonal terrains of the northern plains of Mars in Elysium, Acidalia, and Utopia Planitia as the Martian equivalent of deep water polygonal fault systems of the Earth.

Unraveling the kinematic evolution of segmented rift systems: the Koa'e Fault System, Hawaii.

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Early rift-fault systems comprise an array of fine-scale structures, such as networks of cracks and small displacement faults, forming zones of damaged rock that have properties distinct from the surrounding intact host rock. As the rift system evolves (i.e., increasing displacement and/or fault length), this early-formed damage is commonly reactivated, influencing the distribution and growth of new fractures. Constraining the role of this inter-fault deformation in fault zone development is therefore important to the regional distribution of extensional strains, and the evolving physical and fluid flow properties of the host rock.

In this contribution we use the exceptionally well exposed Koa'e fault system on the south flank of Kilauea Volcano on Hawaii's Big Island to investigate the complex evolution of relay zones. The Koa'e represents an incipient rift zone that links the volcanically active Southwest and East Rifts, accommodating <1% extension at surface, which is driven by gravitational spreading of the volcano's southern flank. The Koa'e system is believed to serve as a conduit for magma propagation and storage, therefore understanding the evolving distribution of the Koa'e extensional system is important to local volcanic hazards, as well as informing flank collapse models.

Structures in a 3 km^2 area of the Koa'e were mapped remotely using high-resolution satellite imagery and aerial LiDAR-derived datasets. Structural maps were then ground-truthed by intensive structural field mapping, using dGPS to constrain fracture distributions to sub-metre precision and accuracy. Field characterisation of fracture and fault sets also included the measurement of displacement, kinematics (opening directions and slip sense), and the length of individual structures. Mapping revealed two dominant trends in fault and mode I fracture orientation: (1) an ENE-WSW (080°) trend that parallels the main Koa'e and east rift axis and displays a dominant NNW-SSE opening direction, and (2) an WNW-ESE (110°) trend of fractures and faults that form a hard linkage between the main 080° bounding faults; opening directions across the 110° fractures are dominantly NE-SW. Aperture (displacement) versus length profiles for the main bounding faults show strong asymmetry and steep gradients, possibly reflecting tip interaction and displacement transfer. The measured fracture distributions and kinematics will be used to populate and test boundary element method-based models to constrain the role of fault interaction in controlling fault propagation during rift evolution.

Characterising pseudotachylyte across the Outer Hebrides Fault Zone, Scotland: an investigation into coseismic deformation

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The Outer Hebrides Fault Zone in NW Scotland presents one of the finest examples of coseismic slip preserved in the geological record, with pseudotachylyte – a frictional melt – being widespread, multiphase and heterogeneous in terms of orientation and geometry. Structural and petrological analysis of the pseudotachylyte therefore allows us to investigate the evolution of this long-lived, crustal scale fault zone and assess how controls on seismogenic reactivation may have varied over an interval of several hundred million years, and through a range of crustal depths. In addition, constraints on pre- and co-seismic temperature and pressure conditions will advance our understanding of the resulting spatial and temporal distribution of deformation mechanisms throughout the fault zone.

A sampling transect perpendicular to the main fault was undertaken across South Uist to capture the variety in character and volume of pseudotachylyte, crossing the main fault zone and continuing some few kilometres into the footwall where large volumes of frictional melt are still found. These samples have been examined under the optical and scanning electron microscopes to identify patterns in microstructures and chemical composition that, within their larger-scale structural context, will provide clues to the mechanisms and controls of generation and distribution. In particular, the question of whether pseudotachylyte found well away from the main fault was generated in scattered local events or alternatively transported there through a highly permeable damage zone may be addressed through this approach. Further work will attempt to constrain the depths of formation and identify how this affects the nature of the pseudotachylyte produced.

Evolution of Sandstone Porosity During Normal Faulting

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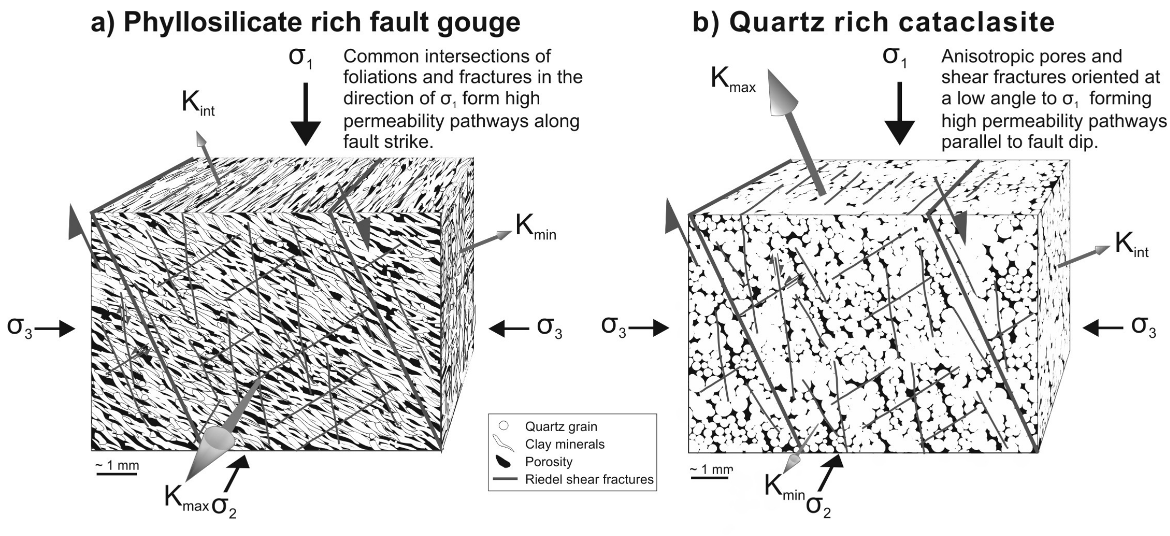
Porosity is a measure of a rock's ability to store fluid. This is important as fluid storage capability determines the amounts of valuable resource fluids such as water or hydrocarbons that can be accumulated. Corresponding measurements of pore connectivity and permeability are also essential to understand patterns of fluid migration and predict where accumulations will occur. As well as providing exploitable reserves, accommodation of fluids in pores can influence the strength of a material. This is particularly relevant in rocks where burial of porous bodies at confining pressures increases the pore fluid pressure, thereby altering geomechanical strength. Mechanical responses to pore fluid pressure change (i.e. effective stress) may be variable depending on the geometry of pores in relation to the principal stresses acting on the rock.

In this study we quantify the development of porosity and pore geometries in core plugs and thin sections sampled from a normally faulted quartz arenite. Results show a decrease in porosity as increasing fault displacement collapses original pores and cataclasis reduces grain size. Analysis of pore geometries shows development of new fault-related pores with common shapes *and* orientations. Fault related pores are elongate and anisotropic, frequently oriented at a low angle to the maximum principal stress (σ_1) and parallel to fault dip. Measured core plug permeabilities show anisotropy of permeability in three orientations to the fault with K_{max} also oriented parallel to fault dip.

Previous studies of fault-induced permeability anisotropy in clay-rich fault rocks suggest that preferential flow directions are controlled by intersections of fault-related microstructures such as the phyllosilicate foliation and Reidel fractures (Fig 1.a). We propose a new model that shows how anisotropic pores and preferential flow directions could be produced in cataclastic quartz arenites by compaction and reorganisation of grains through shearing and cataclasis, creating anisotropic pore structures and dilatant microfractures (Fig 1.b).



The interaction between polygonal faults and hydrothermal vents

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The interaction between polygonal faults and hydrothermal vent complexes have been shown to produce enigmatic radially aligned polygonal fault zones. These radially aligned fault zones have been described in previous studies in several basins across the globe but the mechanism for their formation is poorly understood. This study uses well imaged, 3D seismic data from the Norwegian Margin to investigate radially aligned faults around 24 vents occurring in association with a single sill. This study reveals that the dimensions of radially aligned polygonal fault zones are highly variable and that these variations do not correspond directly to vent or mound dimensions. The size of the radially aligned polygonal fault zone appears to be influenced by reflection characteristics within each vent complex.

This study proposes that the variation in reflection characteristics relates to variability in vent composition, with vents associated with a single sill containing different facies. The 1D consolidation of the sediment pile, creates a forced fold through differential compaction around the vent. It is suggested here that the size of the radially aligned fault zone is governed in part, by the width of the vent and also compositional varaition within the vent itself. These differing vent facies respond to loading in differing degrees by either yielding or resisting compression, depending on the vent fill. Vent fill that displays enhanced reflection characteristics have the largest radially aligned fault zones and are interpretted as being more cemented or containing magmatic material. These 'harder' vents resist compaction and create pronounced forced folds. This mechanism for creating an incipient radially aligned polygonal fault zone is proposed to be similar to that of a passive salt diapir penetrating its overburden.

A fossil-geothermal reservoir: relationships between fractures and palaeofluids in the Terra Nera area (Elba Island, Italy)

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An integrated study based on structural geological analysis and fluid inclusion microthermometric data was carried out on the Early Pliocene Terra Nera fossil-geothermal field, located along the eastern coast of Elba Island. The chosen area is typified by the presence of the Zuccale Normal Fault detachment. Within the damage zone of this detachment, four vein systems, mainly made up of quartz and hematite, have been recognized.

These systems comprise a set of strike-slip veins, and extensional veins, oriented about N170 and N60, respectively. Each of these systems is interconnected by a set of linkage veins. The veins were produced by coeval extensional and dextral transtensional strike-slip movements. This network of veins constrains a minimum value of effective fracture porosity of about 26% (estimated using ImageJ software).

Liquid-rich fluid inclusions were recognized in quartz-gangue, with a homogenization temperature ranging between 265 and 400 °C and an average salinity of 26% wt NaCl eq. Such values are common to both the strike-slip and extensional veins, and are typical of magmatically derived fluids. Microthermometric data constrain fluid temperature conditions to be in the range 490 - 535 °C, while pressure is estimated <240 MPa. Such conditions are typical for supercritical fluids.

This evidence, based on the integration of fluid inclusions data and structural analysis, indicates that a single magmatic fluid flow path ran through the hydraulically connected damage zone of the Zuccale Fault. We further suggest that the study area can be interpreted as a portion of a deep geothermal reservoir close to the heat source, represented by the Porto Azzurro pluton.

Field evidence of top seal failure? The Upper Miocene Sandstone Intrusions and the fracture network of 4-Miles Beach, Santa Cruz, California

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The cliff-line along the northern margin of 4-Miles Beach (about 6.5 km north-west of Santa Cruz, California) exposes an exceptional “pseudo-” three dimensional section of a suite of Upper Miocene sandstone intrusions.

These sandstones intrusions form a system of interconnected dykes and saucer-shaped intrusions within the organic-rich, biosiliceous Santa Cruz Mudstone. The underlying Santa Margarita Sandstone is believed to be the parent unit of this set of sandstone intrusions, and acts also as the reservoir rock in several exhumed oil field in this area.

Sandstone intrusions form a network of mostly tabular dykes, with apertures which range from 15 to 50 cm, and predominant strike toward NE. Colour in sandstone intrusions varies from dark grey to black dependent on the presence of residual oil and bitumen. Dykes exhibit multiple branching into thinner intrusion segments. Saucer-shaped intrusions associated with the dykes commonly show lower apertures than the dykes (ranging from 2 to 8 cm), and appear to be branches of dykes. What is remarkable about this location, is that clearly the larger saucer-shaped intrusions are feeders into smaller, which are located topographically above and within the diameters of the larger saucers. Nesting, branching and re-joining is characteristic of all the saucer-shaped intrusions. The margins of saucer-shaped intrusions are often wavy and/or stepped. Because both dykes and saucer-shaped intrusions are sharp and continuous, it is likely that these features were generated simultaneously. The complicated structure of this intrusive network indicates excellent local three-dimensional interconnectivity.

A number of faults have been observed on the cliffs along the beach. They cut sandstone intrusions continuing into the host mudstone, and show the characteristics of a transtensional movement and typically strike to the north-west.

The entire outcrop of Santa Cruz Mudstone is characterised by a pervasive extensional fracture system that form a joint set striking predominantly north-east, and having all the features, i.e. plumose structures, hackles and hackles fringes, that are typical of a tensile failure. Bitumen and calcite commonly form fractures fills. Locally, joints cut the intrusion, and this have a greater effect on the saucer-shaped intrusions then on the dykes. Joint formation occurred after the intrusions and the lack of the jointing intensity between the host strata and the intrusions is maybe related to the competence of the latter. Systematic joint sets in the Santa Cruz Mudstone form a steeply dipping, approximately orthogonal, set striking north-east and north-west. The north-east set is the most prominent with the north-west joints usually terminating into it.

The unique exposure of the sandstone intrusion network observed at 4-Miles Beach may be regarded as an analogous to the sand injectite systems observed on numerous seismic profiles, and therefore it can be helpful to understand geomechanical and hydraulic processes in the subsurface.

Fracture patterns and controlling factors in porous sandstones, south central Pyrenees, Spain

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Understanding evolution of fault geometry and hydromecanical properties is essential in order to better constrain fluids flow circulations in the continental crust. The knowledge of faulting in analogous reservoirs is particularly important in silicoclastic context, because of the high value of natural porosity and the impact of faulting on porosity and permeability. Depending on the type of faults, deformation in sands and sandstones reservoirs can produces barriers or conduits for fluids.

In this contribution, we focused on an silicoclastic analogous reservoir localised in south central Pyrenees (Spain), named the Aren group, where deformation is recorded by different type of faults. The Aren group is located on the front of the Boixol thrust, on the southern side of the San Corneli anticline. The outcrops are localised in 3 different areas, comprised between the towns of Aren, Tremp and Isona. Depending of the outcrop, we identify presence of joints, deformation bands and some few sites where both of them are recorded in the same unit. We present a complete field study, based on two different field mapping methods: (i) field photomosaiques and associated detail 2D mapping; (ii) linear scanlines along deformed outcrops. These two different methods, applied around ten outcrops allow us to obtain: (1) 30 meters squares of 2D detailed maps of fractures and linkage information; (2) 90 linear meters of fracture density vs. distance all along the outcrop for each type of fracture. Field measurements and quantification was completed by a systematic sampling, in order to give an access to (i) microtectonic elements and fine characterisation of the different fault types by SEM observations; (ii) a porosity quantification of host rock and fault zones based on the SEM pictures.

These detailed analytical methods demonstrate the evidence of two different type of deformation and can allow us to determine the corresponding controlling factors. These geological factors are essential for determine the bulk permeability of the reservoir, by understanding the growing process for obtain conduits or barriers. In addition, a future work could show some evidence for a transition in growth mechanisms from the deformation bands to the joints, and especially to the mode I cracking process.

Quarry design in fractured rock volumes; rock strength and slope stability at Croft Quarry

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All quarries involve manufactured slopes, including the excavation pits, and placed extracted materials. Hard rock quarrying requires significant fragmentation of the rock volume for extraction, including drilling, rock crushing, and blasting. The target rocks are typically jointed, either naturally, or following unroofing and blasting during excavation, which may be variably oriented relative to the manufactured slope. Rock strength is therefore strongly influenced by the density, continuity, and orientation of these joints relative to the evolving manufactured slope, hence characterisation of the jointed rock properties is crucial during quarry design. Croft Quarry in Leicestershire, targets Late Ordovician (500-450 Ma) banded tonalite for extraction, which is unconformably overlain by Triassic Mercia Mudstone (251-199 Ma) The tonalite is part of an approximate 14 km wide pluton which links to a series of small batholiths at depth, as part of the 'South Leicestershire Diorites'. Recent excavation of the tonalite has led to slope failure within the quarry, along natural joint planes. This project aims to assess the orientation of joint planes within the quarry, and characterise the tonalite strength anisotropy resulting from these discontinuities. Structural mapping reveals the tonalite is host to seven main joint orientations, which are variably dominant within the quarry, defining seven structural zones. We analyse the physical properties of the 3D fabric of the tonalite samples to assess the strength anisotropy due to foliation and or microcrack/porosity orientations, which would reflect the joint properties. Samples from these identified zones will be used to parameterise rock properties, such as density, effective and total porosity, and compressive strength (test point load), as a function of orientation relative to the joint and microfracture sets. Selected samples will be loaded under uniaxial configuration so that stress-strain relationships (up to failure), as well as the type of deformation/fracturing can be described. Results of the study will have direct implications to quarry excavation techniques and sequencing, particularly in terms of bench distances and quarry face orientation.

Structural architecture of the NW Borneo deep-water fold and thrust belt and the underlying causes of lateral (along strike) structural variability.

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Lateral structural variability of fold–thrust belts and its associated up-dip extensional structures often reflects lateral variations in the thickness of the deforming wedge and interaction with pre-existing structures. The Miocene to Recent deformation in the offshore NW Borneo wedge is a spectacular example of gravity driven deformation in a deepwater setting. The margin was traditionally divided into three major structural provinces based on structural styles imaged in seismic data: an inversion province in the inner shelf and onshore part; an extensional province in the outer continental shelf and upper slope; and a compressional province in the lower continental slope and uppermost rise. These structural provinces are characterized by (1) NE-SW and N-S striking inverted seismic scale growth faults preserving thick depocentres associated with folding, uplift and erosion in the inverted province; (2) regional (basinward-dipping) and counter-regional (seaward-dipping) growth normal faults associated rollovers, depocenters and mud diapirs in the extensional province; and (3) basinward verging thrust faults (typically imbricated) associated with fault propagation folds and including some detachment folds in the compressional province. Variations in the thickness of the sediment pile across the offshore NW Borneo margin affect the structural architecture of the fold–thrust belt, causing lateral variations in horizontal shortening and the spatial organization of the structures. Thicker sediment piles deform at low slope angles thus creating as a series of widely spaced thrusts separated by wider piggyback basins and higher displacement. Another observation is that the formation of regional (basinward-dipping) and counter-regional (seaward-dipping) growth normal faults is strongly related to regional variations in sediment storage and the presence of pre-existing structures beneath the main depocentre.

Fracture characterisation in folded Torridonian sandstone; an example from the Achnashellach culmination, Moine Thrust Zone, NW Scotland

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Numerous authors have reported patterns of fracture on asymmetric anticlines relating to a combination of structural and lithological controls. Fracture orientations are thought to be controlled by the direction of maximum stress resulting in four main fracture sets on thrust related anticlines. Fracture intensity, length and aperture are thought to increase in high strain zones of these folds, such as the forelimb and close to the active thrust, as well as being influenced by lithological variables such as grain size and mineralogy. Fracture spacing/distribution and clustering are thought to be related to the distribution of strain across the structure.

Here we aim to test these hypotheses using a series of folds and thrusts within the Torridonian sandstone of the Achnashellach culmination in the Moine Thrust Zone of NW Scotland. Preliminary data suggests a correlation between fracture orientation and intensity with structural position in higher strain zones; the data are more variable on lower strain fold backlimbs, suggesting that lithological controls may be more influential here.

Fracture characterisation is important for understanding variations in rock strength and bulk permeability. Our data show significant variations in fracture attributes across small distances indicating that current methods for fractured reservoir characterisation including well log image analysis at widely spaced intervals may not be sufficient to accurately capture the spatial variations.

Monte Carlo or bust! Assessing the probability of failure

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The utility of any predictive model always depends, in part, on the quality of the input parameters. If the information we have about some or all of the inputs is too vague, the model itself may be effectively useless. The Mohr-Coulomb paradigm for rock failure forms the basis for many studies of fault and fracture stability, from earthquake hazard assessment (e.g. stress transfer models), slip and fracture tendency analyses for subsurface reservoirs and borehole stability analysis. Ignoring the inherent physical limitations of the Mohr-Coulomb model for brittle failure, this contribution asks the question: How well can we ever know the input data?

Principal stresses, pore fluid pressure, and rock strength parameters (shear strength, cohesion or friction) all exhibit natural variability. Accepting variations in our estimates of these inputs makes the predictions from Mohr-Coulomb models much harder to interpret. This contribution uses Monte Carlo simulations based on knowledge gleaned from geomechanical analyses of stress, pressure and strength in the Niger Delta and the North Sea to assess the impact of variable input parameters for the Mohr-Coulomb model. This work also suggests alternative ways of dealing with this uncertainty in our quest to make rational and safe predictions about rock failure and fracture stability.

Sill Facies identification and its Implication for the Emplacement of Sill Complexes, Faroe-Shetland Basin, NE Atlantic Margin.

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The recent availability of high-quality 3D seismic data from the rift basins of the NE Atlantic Margin has enhanced our understanding of the 3D geometry and emplacement mechanisms of sill intrusions associated with volcanic rift margins. In this study high-quality, 3D seismic data from the Faroe-Shetland Basin has been used to interpret a series of sill facies which are indicative of their emplacement environment, local structural heterogeneities and proximity to the spreading centre. Three distinct sill facies have been identified. The first are long, tabular intrusions, which are flat and often follow bedding planes. These intrusions have volumes up to $7km^3$ and form through continuous magma supply consistent to their proximity to the spreading ridge. Further landwards, classic saucer-shaped sills begin to develop; these form complex interconnected networks and appear to be emplaced as single pulses of magma, they decrease in size and frequency at shallower crustal depths. The final sill facies are small, discontinuous intrusions which form at the furthest extent of sill intrusion away from the spreading centre and are the product of limited magma supply and significant syn-rift fault interaction. The three sill facies represent a change in emplacement style with increasing distance from the spreading centre and can be considered a kilo-metre scale refinement of the broad landward flow volcanic facies established by Planke et al. (2000).

Sill propagation in mechanically layered media: stepped and transgressive sills in the Faroe Islands

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Igneous sills represent an important contribution to upper crustal magma transport, acting as magma conduits and stores (i.e. as sill networks, or as nascent magma chambers). Complex sill-network intrusion in basin settings can have significant impact on subsurface fluid flow (e.g., water aquifer and hydrocarbon systems), geothermal systems, the maturation of hydrocarbons, and methane release. Models for these effects are critically dependent on the models for sill emplacement. The purpose of the present paper is to highlight an exemplary staircase-geometry saucer-shaped sill in the Faroe Islands, emplaced into a layered sequence comprising lava units and volcaniclastic units, which records features associated with sill propagation and inflation. The sill covers about 17 km^2, with a vertical extent of about 480 m. It can be separated into two broad saucer shapes: the NW and SE segments. Sill thickness ranges from 20-30 m in the NW segment, and 40-50 m in the SE segment. Pre-erosion estimates for the sill suggest it covered about 45 km^2, at a volume of ~2 km^3. Erosion has resulted in variable incision through the stratigraphy, but importantly, in places, has stripped host units back to reveal the sill top surface. Mapping of the top and bottom sill contacts where erosion cuts through the sill, confirms that the topographic expression observed represents primary intrusive features, rather than differential erosion. Sill segments show a prominent staircase geometry, with flat sections connected to risers that have a maximum dip of 58°. Steps are broadly circumferential to the respective main saucer shapes, and occur at two general scales: (1) 40-60 m width flats separated by 5-25 m vertical rise; and (2) 300-330 m width flats with about 60 m vertical rise. The intruded sequence at these levels is dominated by 1-3 m thick compound lava units. Although flat sections correspond to lava unit interfaces, or to volcaniclastic units, they also transect a great number of units, and unit interfaces. Sill geometry indicates that the sills intruded as lobes, which inflated initially as unit-parallel sheets, before developing transgressive steps, which again inflated as lobes before linking to create a through going sheet. The scale of the sill riser sections indicates that mechanical layering is not the primary control on their geometry. Rather it is probably the development of stress anisotropy at the sill tips, caused by overburden uplift and flexure, that promotes transgression: as steps propagated initially as thin lobes, stress anisotropy diminished, at which time mechanical layering becomes the primary control. Results have direct implications to sill emplacement and propagation mechanisms, as well as to geophysical imaging and interpretation of sills in basin settings, particularly where individual unit thicknesses are below seismic resolution.

Accommodation and deformation structures associated with the emplacement of the Trachyte Mesa Intrusion, Henry Mountains Utah

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The Tertiary igneous intrusions of the Henry Mountains, Utah, are the type locality for 'laccolith' intrusions; the term 'laccolite' coined by Gilbert in the late 1800s. The Trachyte Mesa intrusion, the most distal satellite intrusion to the Mt Hillers igneous complex, is an elongate intrusion trending NE-SW, concordant with the Entrada Sandstone it intrudes. The intrusion is comprised of multiple, stacked intrusive sheets. The excellent 3D exposures which cross-cut both intrusion and host rock make this an ideal place to study emplacement-related deformation and emplacement mechanisms. Field mapping and detailed structural data collection studies were focused on the southern end of the NW margin of the Trachyte Mesa intrusion as this is where the host rock-intrusion contact is best exposed in outcrop.

Distinct structural domains were identified within the host rock that reflect both temporal and kinematic variations in deformation. Three deformation phases are identified, interpreted to be pre-, syn- and late-emplacement structures. A background set of deformation bands (phase 1), trending oblique to the intrusion margin, is apparent across the entire area. A second set of deformation bands (phase 2) overprint the early phase. These are characterised by conjugate deformation bands that parallel the intrusion margin, and increase in intensity and spacing towards the intrusion. Within this same zone a series of steep dip-slip (extensional and reverse) faults, striking parallel to the intrusion margin, are apparent. These faults are observed at the tip/ termination of intrusive sheets. Offsets on bedding planes and slickenfibres are preserved on the calcified fault surface and show dominant down to the NW fault kinematics. The throw is similar to the thickness of the intrusive sheet it is associated with. Due to their spatial, kinematic and overprinting relationships we interpret these to be linked to the emplacement of the intrusive body. Mapping of these faults along strike, away from the exposed contact zone, reveal an arcuate trend that appears to match the previously proposed curved nature of the 'lobe'/promontory of stacked intrusive sheets emanating from of the main intrusion. Magma can also be seen intruding along some of these faults: this "sill-climbing" is good evidence that this extension is syn-emplacement. Overprinting all other structures, are two sets of tensile joints (phase 3), often infilled with calcite crystals. These occur over the top surface and lateral margin of the intrusion. These joints strike both parallel and perpendicular to the margin of the intrusion.

Extensional strain parallel to the intrusion margin is consistent with a two-stage growth (1. radial; 2. vertical) for the emplacement mechanism, with the magma spreading laterally as a thin sill, then inflating upwards, jacking up the host rock along brittle normal faults.

Day 2

Tuesday 7th January, 2014

Constraining the ages of polyphase fault reactivation of the Gavilgarh-Tan Shear Zone, central India using laserprobe 40Ar-39Ar dating of pseudotachylytes

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The Gavilgarh-Tan shear zone (GTSZ, Fig. 1), central India provides an excellent opportunity to carry out infra-red laserprobe40Ar/39Ar dating of a variety of fault rocks generated across the frictional-viscous (brittle-ductile) transition zone during the multiple reactivation and progressive exhumation of this crustal fault (Fig. 2). The GTSZ initially experienced ductile deformation at > 15 km depth forming mylonites which yield early Neoproterozoic (ca. 880 Ma) ages. These were overprinted by two distinct sets of pseudotachylytes. An early dextral set, formed at ca. 11-15 km depth with a local mylonitic overprint, give a late Neoproterozoic age (ca. 672 Ma). A later sinistral brittle set yield Ordovician ages (ca. 459 Ma) and represent possibly the first record of Pan African tectonic activity in Central Indian Tectonic Zone. A final phase of brittle faulting is broadly post-Cretaceous as it cuts the Lameta Formation and the Deccan Trap flows and the occurrence of active geothermal springs along some faults may indicate further neotectonic activity. Our findings demonstrate that the GTSZ has a long history of repeated tectonic rejuvenation from the Neoproterozoic up to at least the Cenozoic. They also further demonstrate that the 40Ar/39Ar laserprobe dating tool can be useful for determining ages of overprinting deformations in reactivated crustal-scale fault zones, provided the age data are carefully constrained using detailed field and microstructural observations.

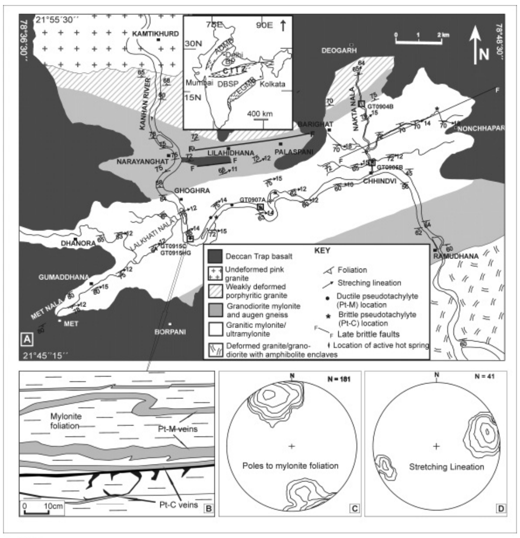

Fig.1:

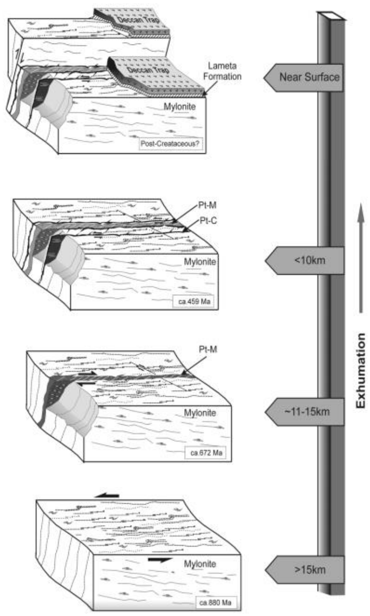

Fig. 2

Remote sensing image analyses to decipher trend of lineaments at Mount Abu Granitoid, Rajasthan (India)

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Automatic lineament identification by edge detection technique is popular in remote sensing studies because of its applicability in diverse geologic/topographic/geomorphologic settings. To distinguish artificial linear features (rail lines, roads etc.), images are to be cross-checked. We used LANDSAT-TM satellite data to identify and map lineaments in Mount Abu region, Rajasthan, India. Post-Delhi Granitoids and Granites, equivalent to Erinpura Granite, are exposed at Mt. Abu. It is also a part of South Delhi Fold Belt. The Delhi Supergroup rocks are exposed with ~ NE trend for > 700 km. It consists mainly of clastic and chemical meta-sediments that folded tightly into regional synclinorium. We enhanced the image by histogram equalization and linear enhancement. Supervised Classification on NDVI image pointed out land cover, and lineaments were inspected visually. Gaussian Blur was applied on Band 5 (SWIR) of LANDSAT-TM satellite image to smooth the image. Canny Edge Detection Algorithm aided lineament identification. Finally, SRTM allowed visualization of lineaments. Lineaments detected by these techniques match each other. Processed LANDSAT-TM images in the Mount Abu region show that the general topographic features trend NE. The structural features/ lineaments trend NW. The latter matches with that of the Mount Abu-Bharatpur regional lineament.

Morphotectonic analysis for a strike-slip fault at the southeastern plunge of Bashiqa anticline

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Sedimentation beds and drainage pattern offset took place predominantly at the southeastern plunge of Bashiqa anticline and this indicates to occur shear stress at this area represented by a strike-slip fault, while (Salih & Al-daghstani,1991) determined this fault as a thrust fault toward southeastern with a linear trend northeastern – southwestern; therefore, this study will update the geological information for this fault depending on the morphotectonical evidences which are included by visual interpretation of the satellite images, adding to the stress analysis for the study area. The determination of this strike-slip fault acting as an efficient geological factor at this plunge of the anticline for any neo-tectonic activity.

Characterising the deep structure of an exhumed ductile shear zone via EBSD: The Uludağ Massif, Turkey.

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Geophysical models that explore the deep rheology of continental-scale fault zones often lack realistic physical parameters that define the actual behaviour expected for a specific fault. This study aims to bridge the gap between geophysical- and geological-derived seismic models of continental scale fault zones by providing lithology and deformation state specific elastic properties from an exhumed ductile shear zone in north-central Turkey. The Uludağ Massif represents a mid-crustal section of the dextral strike-slip Eskişehir shear zone, which was active during the Oligocene and accommodated ~100km of displacement with a component of late oblique-normal slip. The exhumed Massif consists of high-grade metamorphic rocks belonging to the Uludağ Group, thought to be 'post-Ordovician' in *protolith* age, pierced by the Central and South Uludağ granites in the Oligocene. The elastic and hence seismic properties across the ductile Eskişehir shear zone can be estimated from the crystallographic preferred orientation (CPO) of individual and combined mineral phases measured via electron back scattered diffraction (EBSD) in the scanning electron microscope (SEM). Elastic properties determined from CPO will be used to populate seismic models with realistic values to investigate their impact on the seismic response. The preliminary data from the two field seasons and analysis of a small section of the 177 samples collected to date will be presented. The study forms part of larger project on the North Anatolian Fault Zone (NAFZ), for which the Uludağ Massif provides a mid-crustal field analogue. Eventually, the synthetic seismic response obtained from CPO analysis will be used in conjunction with data obtained from a dense seismic array across the NAFZ to better understand the 3D dynamics of this major continental-scale fault zone.

Anisotropy of permeability in mylonites

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Mylonitic ductile shear zones get exhumed into the brittle upper crust and may act as either conduits or barriers to fluid flow. These rocks are often highly anisotropic in terms of fabric or texture, but also in their mechanical properties such as strength and elasticity (acoustic velocity). This contribution presents new laboratory data on the permeability of a diverse range of mylonites from outcrops in Scotland, Italy and Corsica. Permeability has been measured on core plugs (20 mm and 25.4 mm in diameter) using the steady state method and with nitrogen as the pore fluid. Tests were carried out at confining pressures up to 200 MPa, equivalent to a maximum depth of about 6-8 km. Preliminary results show distinct anisotropy of permeability which persists to elevated confining pressures. The direction of maximum permeability lies in the foliation plane but perpendicular to the mineral stretching lineation. The direction of minimum permeability is oriented normal to the foliation. The direction of intermediate permeability lies sub-parallel to the lineation in the foliation plane. This pattern of anisotropy can be related to textural elements visible in thin sections. Anisotropic permeability has been widely reported from clay-rich fault gouges, and more recently from cataclasites derived from sandstones. The presence of significant anisotropic permeability in mylonites has consequences for our understanding of fluid flow patterns in the subsurface.

Modelling seismic velocity anisotropy in polymineralic evaporites

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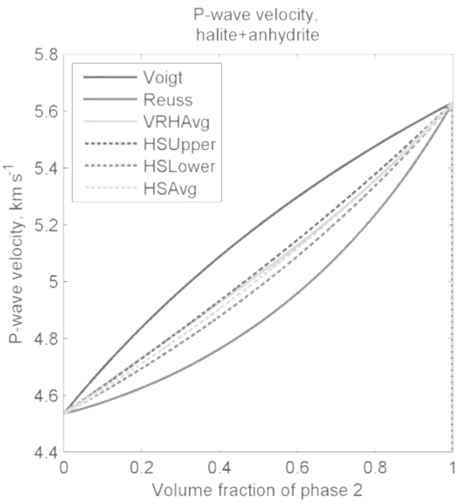
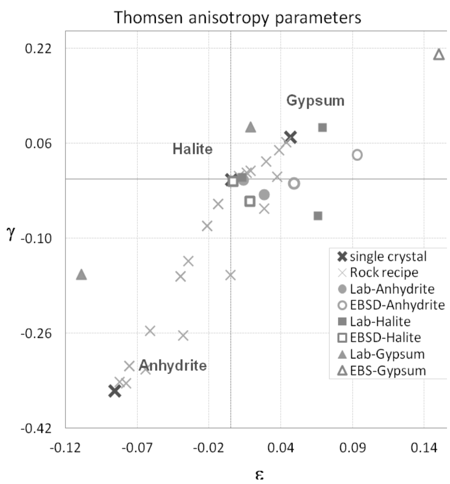
Halite is often the main constituent of salt deposits in the subsurface. However, evidence from the heterogeneity and complex internal structure of natural evaporite rocks indicates that there are other important mineral phases in salt deposits. These can include anhydrite, gypsum, dolomite, carnallite, sylvite and clay minerals, each of which has different elastic properties. Each of these mineral constituents can also align in various ways as a result of salt flow. Thus, the relative contribution of each mineral phase – including their preferred orientation – to the overall elastic and mechanical behaviour of the rock needs to be quantified. Detailed characterisation of the elastic properties of evaporitic rocks is essential for the exploration of complex salt bodies in the subsurface.

We modelled polymineralic evaporite rocks via an averaging method to investigate the effect of various minerals on the bulk elastic properties of salt deposits. Using the published elastic properties of single crystals for the selected minerals and their volume fraction only, and ignoring their crystallographic orientation, we calculated the lower and upper bounds of the elastic moduli of evaporite rocks. Then, by including different crystallographic preferred orientations (CPOs), we calculated the anisotropic seismic velocities of synthetic composite mixtures. We used the resulting elasticity tensors to assess the levels of anisotropy in evaporite rocks in terms of Thomsen anisotropy parameters. Finally, we compared the velocity anisotropy predictions with those measured in the lab on outcrop samples, for which we used ultrasonic velocity measurements, optical microscopy and EBSD data. Because the presence of more than one evaporite in salt deposits produces significant anisotropy, errors may be introduced when describing the behaviour, for instance, of elastic waves in natural salt in the subsurface. In which case, seismic images may be improved by the incorporation of anisotropy in evaporites.





New Insights on the Continental Oceanic Boundary of the Western Greenland Margin

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This study investigates the crustal structure of the Western Greenland margin by integrating gravity and magnetic modelling with seismic reflection data interpretation. Seismic interpretation of 2D reflection profiles along the entire West Greenland Margin from Labrador Sea, Davis Strait and Baffin Bay was undertaken to identify sedimentary and structural component of the margin. Interval and prestack velocities from five wells were used to generate representative depth-converted seismic profiles from Baffin Bay, Davis Strait and Labrador Sea respectively. In addition, Gravity and magnetic modelling of three representative profiles was undertaking using Geosoft's Oasis Montaj™ software, with an initial assumption of a root to moho depth of 30km. Notably, our interpretation demonstrates the presence of a transition zone in Baffin Bay, Labrador Sea and probably Davis Strait from the seismic reflection characteristics. In addition there is a good match recorded between observed and calculated gravity anomalies and magnetic anomalies. All of the integrated data interpretation supports the location of oceanic crust, transition zone and continental crust. Moreover, in these areas we used the vertical derivative of the magnetic data to better define oceanic lineaments and depth to source of magnetized bodies (e.g. dikes); in particular we identified the extinct spreading axis between Canada and Greenland.

The NW-SE magnetic lineaments are presumably parallel to an extinct spreading axis between Canada and Greenland. The lineaments are interpreted into onshore areas and contrast to older NNW-SSE lineament of ~27 chron. The absence of clear cut magnetic anomalies in the Baffin Bay region indicate the existence of serpentinised mantle underneath the continental crust and ultraslow seafloor spreading in this region. This study has provided additional information on the nature of the transition between ocean-continent in the western Greenland.

'Nyalam Detachment', 'Nyalam Shear Zone' and 'Nyalam Thrust' within the Greater Himalayan Crystallines, south central Tibet

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Three meso-scale structural elements have been described near/away from the village Nyalam in the Greater Himalayan Crystallines (GHC), south central Tibet. These are a detachment, a shear zone and a thrust. The first one of these, the 'Nyalam Detachment' (ND), ~ 30 km N to Nyalam, is a continuation of an extensional ductile top-to-N/NE shear zone that demarcates the northern/upper boundary of the GHC [1,2]. The ND consists of a 300 to 400 m thick mylonitized zone with various ductile shear senses indicators [2,3]. The N/NE shear was active between 14.8-16.1 Ma [4], and stopped by ~ 13 Ma [3]. A different age of activation of the STDS was also deciphered viz. 17-15 Ma [5]. The cooling history of the ND resembled that of the GHC [4]. Whether directional progressive change in age of activation inside the ND took place is disputed: compare [2] and [5]. Petrologic significance of the ND is available elsewhere: at [6].

Z. Xu and others reported both top-to-W shear and top-to-E shear from the central GHC and considered the region to be inside the ND [7]. However, they later pointed out that these shears occur south to ND, inside the GHC, and within what they called the 'Nyalam Shear Zone' (NSZ) [8]. Their U-Pb date constrained a short span of ductile shear of the NSZ to be within 28-27 Ma [8]. They deciphered pure shear from the NSZ where the two opposite shears developed simultaneously [8].

Very recently, an out-of-sequence thrust was demarcated inside the NSZ, and was named as the 'Nyalam Thrust' (NT) [9]. The NT is located ~ 2 km S to Nyalam village, demarcates the GHC-upper at north from the GHC-lower at south, activated at ~ 14 Ma onwards and demonstrates a top-to-S sense of shear and NNE plunging lineations [9]. The NT was deciphered to be the southern boundary of a crustal channel extrusion flow 'restricted' in the northern portion of the GHC [9]. Thus, summarizing everything, the GHC in south central Tibet consists of a northern boundary of simple shear, and a central portion of pure shear along with an out-of-sequence thrust. As per fig. 3 of [9] and fig. 5a of [8], NT plots within the NSZ.

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The role of shear zones in the spreading of the orogenic crust – an example from southern Finland

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In orogenic belts, crustal thickening precedes rheological weakening of the middle and lower orogenic crust leading to lateral spreading and, ultimately, to the collapse of an orogen. Such spreading has been identified beneath e.g. the Tibetan plateau and the Alps. Details of this spreading are, however, still not clear. The dynamics of and the more detailed strain distribution during the spreading are among the still open questions.

Recent studies have implied that syn-orogenic lateral spreading occurred in the middle crust of the Palaeoproterozoic Svecofennian orogeny. The Svecofennian middle crust is presently exposed, offering an analogue to younger orogenies, and a good opportunity to investigate the architecture and mechanisms of orogenic spreading. Furthermore, the crust is imaged by the Finnish Reflection Experiment (FIRE) that was designed to image the major crustal structures in Finland. Attribute analysis of the seismic data has revealed detailed information about the deformation fabrics related to the spreading within the crust. Previous interpretation of the seismic data show that the extension/lateral flow of the orogenic middle crust was mainly accommodated by km-scale S-C' structures. The structures form a penetrative deformation fabric that overprint the older, compressional structural grain.

The extensional features observed in the seismic are correlated with outcrop observations. 1-2 km thick, granulite facies shear zones, observed in the field and correlated with the seismic data, play a central role in the lateral extension of the orogenic crust. In this contribution, we present geochronological data from some of these shear zones, in order to establish the timing and the role of the shear zone activity with respect to the overall orogenic development. We discuss the seismic interpretation and our new geochronological data from the extensional shear zones in the wider context for geometrical models for and strain accommodation during lateral spreading/mid-crustal flow. We focus on the implications of the results on i) the timing of orogenic spreading with respect to the crustal thickening (mid-crustal flow vs. collapse); and ii) models of strain accommodation and partitioning during orogenic growth and syn-kinematic lateral spreading.

The early and middle stages of uplift of the northeast Tibetan Plateau

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The Qilian Mountains in the northeast Tibetan Plateau represent one of the most active regions of the Plateau and may provide a type example for the evolution of its older regions. The Qilian Mountains are an orogenic collage of island arc derived meta- volcanic and sedimentary rocks, accreted to the North China Craton during the mid-Palaeozoic. Deformation and mountain building associated with the Indo-Asian collision have been active in the region since the early Miocene and are characterised by the formation of fold-thrust mountain ranges which splay south-eastwards from the sinistral, northeast trending Altyn Tagh Fault (ATF).

This project investigates the extent of inherited structural and lithological controls on the post-Oligocene tectonics around the Changma Basin (Fig. 1) at the very northeast corner of the Plateau, where the ATF forms a triple junction with the Qilian Nan Shan. Our research involves synthesis of previous geological and geophysical data, remote sensing analysis and structural mapping along key transects.

The Changma Basin is bound to the north by the Yumen Shan and the ATF, and to the east by the Qilian Nan Shan. Data collected from theses ranges suggest that present deformation occurs on the range-bounding thrusts as well as on intra-range thrusts both within and below thick limestone units. In the region east of the triple junction, northeast-verging folds and basement pop-ups structures are forming in the cover sediments in response to transpression against the ATF. The Changma Basin itself is internally deforming and inverting as the Yumen Shan back-thrusts due to compression against the ATF. Meanwhile, the basin is being infilled by sediment eroded from the surrounding ranges, and is only kept at a low elevation by the erosive power of the Su Le River which drains a large area of the northeast Tibetan plateau and is one of the few external drainages in the region.

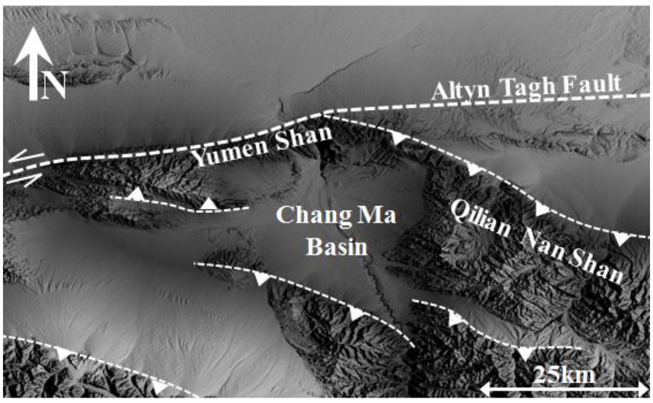

Figure 1; Topographic map showing the ranges and major faults surrounding the Changma

Using these observations we suggest that the early and middle stages of plateau uplift can be separated into three main stages; compression against the ATF resulting in folding of the cover and localised basement thrusting; extensive basement thrusting raising high mountain ranges; and deformation and inversion of intermontane basins due to compression and range back-thrusting.

Keywords: Northeast Tibet, Altyn Tagh Fault, Qilian Shan, plateau growth, triple junction, basin inversion.

Reservoir quality of Kurra Chine and Sehkaniyan Formations, Zagros Fold and Thrust Belt, Kurdistan

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The Zagros Fold and Thrust Belt of Kurdistan (NE Iraq) hosts a prolific hydrocarbon system. Most exploration wells target the Kurra Chine Formation (Upper Triassic) and/or the Sehkanian Formation (Lower Jurassic), where hydrocarbon production mainly comes from fractures. We investigate the fracture characteristics of these units using selected outcrops around the Gara, Ora and Ranya anticlines (Kurdistan). In addition, we report petrophysical properties - porosity, permeability, acoustic velocity - of both units.

Both units have undergone multiple phases of deformation by folding and thrusting. This is characterised by tectonic stylolites, tectonic breccias, bitumen inclusions, and late diagenesis. The best reservoir quality is often found in areas associated with replacement dolomite i.e. solution vugs and intercrystalline porosity. Fault-controlled hydrothermal dolomite is indicated by saddle dolomite textures. The latter in turn is characterised in thin sections by sweeping (wavy) extinction in cross polars and abundant fluid inclusions. Hydrothermal dolomites form in close association with fault systems, generally with some strike-slip component.

The reservoir properties of the Kurra Chine are variable due to irregular dolomitisation of the carbonates. Increased permeability may also be attributed to fractures. The Upper Kurra Chine consists of naturally fractured dolomites. The rocks of the Sehkaniyan Formation have good reservoir quality, predominantly when hydrothermally dolomitised. In the current study, porosities of the Kurra Chine Formation ranging from 0.8% to about 30% at outcrops, and permeabilities show a range of five orders of magnitude (0.0003-20 mD) and an average very low permeability at high pressure (0.0001 mD). Porosities of the Sehkaniyan Formation varying between 1% and 8%, and permeabilities show less variation about three orders of magnitude (0.001-1.5 mD) and an average very low permeability at high pressure (0.0002 mD). The velocity-porosity data show separate trends between primary and secondary acoustic velocities of the Kurra Chine and the Sehkaniyan. This variation in values is attributed to the structural position within the anticlines, stratigraphic level, proximity to the faults and fracture corridors, and overall tectonic deformation from an earlier extensional phase to the flexing of competent limestone units during Zagros orogeny.

The quantitative prediction of radon emanation based on data recorded at Driny Cave, Malé Karpaty Mountains, Slovakia

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The EU-TecNet fault displacement monitoring network comprises more than one hundred subterranean geodynamic observatories sites spread throughout the continental interior of central Europe (www.tecnet.cz). These observatories were initially established in order to characterise ongoing geodynamic activity in the shallow crust. Previously it has been suggested that there may be a relationship between cave radon concentrations and *in situ* fault displacements recorded at Driny Cave, Mladeč Caves, and Bozkov Dolomite Caves (Briestenský et al. 2011a). Here we report a quantitative predictive model for radon emanation based on two years of data recorded in Driny Cave, Malé Karpaty Mountains, Slovakia (Briestenský et al. 2011b). The following time series have been employed as input variables: (i) temperature inside the cave; (ii) the temperature outside the cave; (iii) atmospheric pressure outside the cave; and (iv) cave radon concentrations. In order to accurately correlate the obtained data it is known that two ventilation mechanisms play a significant role: the so-called 'chimney effect' operates during the winter as lighter air is forced into the cave through the lower entrance and this is then expelled though the upper entrance while during the summer the heavier air dissipates through the lower entrance to the cave. On these grounds it has been found that both the instantaneous radon concentration and the radon emanation inside the cave scales with square root of the relative temperature difference ($\sqrt{(|\Delta T|/T)}$). Moreover, it is demonstrated that for the period 2010-2011, our predicted radon emanation peaks show highly significant correlations with the *in situ* fault displacements recorded in the cave - the latter are recorded using three permanently installed three-dimensional optical-mechanical crack gauges (Marti et al. 2013). The reported quantitative predictive model opens the door to the real time detection of radon emanation peaks.

Further reading

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Digital Field Mapping – Enhancing Field Skills?

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Field Mapping is a core component of an undergraduate geology degree and the skills used are considered fundamental for a practicing geologist. We would argue strongly that it is in teaching field mapping and model building skills that the geologist learns to think in three and four dimensions and this leads to a better appreciation of the geometry and scale of the geological structures that will be encountered during an industry career.

The approach that a geologist takes to field mapping has remained largely unchanged over the past century; working from a printed base map and annotating observations on outcrop data and measurement results. More recently the use of hand-held GPS systems to determine geographic location has become commonplace, and a few geologists have also adopted GIS technology on portable devices.

A recent study found that 82% of new students own a smartphone and 20% own a tablet device (UCAS Media, 2013). With this increased availability, and affordability, of smartphone and tablet devices, new methods should be examined for collecting data in the field to ensure that time is spent as effectively as possible collecting useful information and giving more time to think about geological relationships.

This poster will examine the use of new digital smartphone and tablet devices for the collection of geological field data. Apps such as Midland Valley Exploration's *Fieldmove Clino* enable the geologist to use their smartphone as a measuring device instead of using a traditional compass-clinometer. A further advantage is that the field notebook and camera which were are also an essential part of the geologists toolkit are now an integral part of the new technology. However, will a move to digital mapping require the development of new field skills and what are the implications for real time assessment and the critical analysis of field data?

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